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MECHANISM OF FLUOROALKENE CYCLOADDITION
AND α -LACTONE CHEMISTRY

A thesis presented

by

Robert Clayton Wheland

to

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MECHANISM OF FLUOROALKENE CYCLOADDITION

AND α -LACTONE CHEMISTRY.

Professor P. D. Bartlett
Robert C. Wheland

Harvard University
July, 1970

Summary

Thermal cycloaddition of pure cis- or trans- $\text{ClFC}=\text{CFCl}$ to cyclopentadiene simultaneously gives 94-97% of 1,4 adducts with retention of halogen configuration and 3-6% of 1,2 adducts with loss of halogen configuration. Most likely then competition between 1,2 and 1,4 cycloaddition of fluoroalkenes to dienes must be understood in terms of those factors leading to either a biradical 1,2 process or a concerted 1,4 process.

Since dichloromethylenecyclopropane (with olefinic destabilization and rehybridization similar to that in fluoroalkenes) cycloadds 1,2 to butadiene unlike $(\text{CF}_3)_2\text{C}=\text{CCl}_2$ (with electron withdrawal similar to that in fluoroalkenes), it is concluded that the biradical reactivity in fluoroalkenes is to be associated with olefinic destabilization and/or rehybridization.

Destabilized fluoroalkenes $\text{ClFC}=\text{CFCl}$ and $\text{Cl}_2\text{C}=\text{CF}_2$ are shown to readily cycloadd trans-cyclooctene by a biradical mechanism under conditions unfavorable to their addition to cis-cyclooctene or to the addition of analogous normal alkenes $\text{H}_2\text{C}=\text{CCl}_2$, $\text{ClHC}=\text{CHCl}$, and $\text{CF}_3\text{ClC}=\text{CClCF}_3$ to trans-cyclooctene. Since trans-cyclooctene does not have fluoroalkene rehybridization, it seems that olefinic destabilization is a necessary and sufficient condition for biradical reactivity. Use of the Hammond Postulate rationalizes destabilization's acceleration of biradical 1,2 cycloaddition relative to concerted 1,4 cycloaddition.

α -Lactones have been prepared by novel synthetic methods. Photolysis of diphenyldiazomethane in the presence of carbon dioxide or ozonization of diphenylketene affords diphenylacetolactone as an open dipolar species that immediately polymerizes, charge neutralizes by the addition of methanol, or cycloadds hexafluoroacetone (in a direction contrary to that expected on the basis of orbital symmetry). Ozonization of di-*t*-butylketene affords di-*t*-butylacetolactone as a closed three-membered ring compound stable at low temperatures in nonpolar solvents such as CFCl_3 and pentane. Di-*t*-butylacetolactone is attacked α to the carbonyl group by ammonia much as has been postulated for α -lactone intermediates in the solvolysis of α -halocarboxylate anions. On warming di-*t*-butylacetolactone apparently opens to a dipolar ion that polymerizes to polyester or that internally charge neutralizes by formation of olefin plus carbon dioxide, β -lactone, and/or carboxylic acid. The behavior of these α -lactones agrees remarkably well with a crude LCAO-MO calculation.

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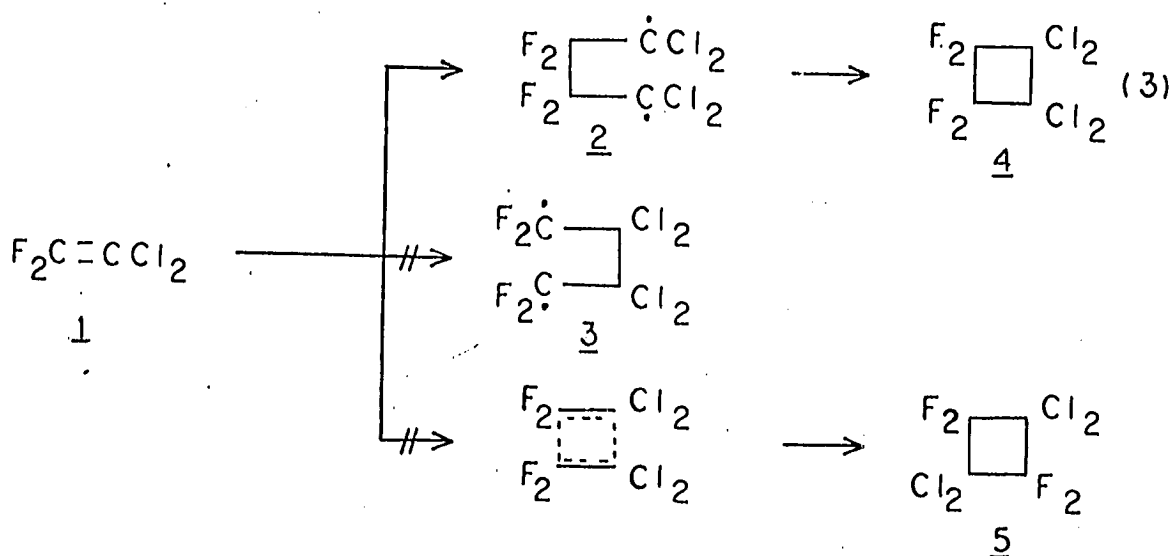
Generous financial assistance was provided by the National Science Foundation from 1966 to 1970.

Mechanism of Fluoroalkene Cycloadditions to Dienes

I. Competition between 1,2 and 1,4 Modes of Cycloaddition

A. Statement of problem

1. Thermal (2+2) fluoroalkene cycloaddition: Fluoroalkenes are now commonly considered to cycloadd (2+2) by way of the most stable biradical intermediate. For example, 1,1-dichloro-2,2-difluoroethylene 1 (hereafter designated 1122) and chlorotrifluoroethylene dimerize by second order kinetics¹ through intermediates of type 2 rather than 3 since chlorine stabilizes a radical center roughly 4 kcal/mole more than does fluorine.² In contrast if dipolar effects were dominant one would expect the negative end of one fluoroalkene molecule to align itself with the positive end of a second fluoroalkene molecule ultimately giving the head-to-tail dimer 5 rather than



1. a/ B. Atkinson and M. Stedman, J. Chem. Soc., 512(1962). b/ J. R. Lacher, G. W. Thompkin, and J. D. Park, J. Am. Chem. Soc., 74, 1693(1952).
2. a/ J. D. Roberts and C. M. Sharts, Org. Reactions, 12, 1(1962). b/ C. Walling, Free Radicals in Solution, John Wiley and Sons, Inc., New York, 1957. c/ F. W. Stacey and J. F. Harris, Jr., Org. Reactions, 13, 150(1963).
3. A. L. Henne and R. P. Ruh, J. Am. Chem. Soc., 69, 279(1947).

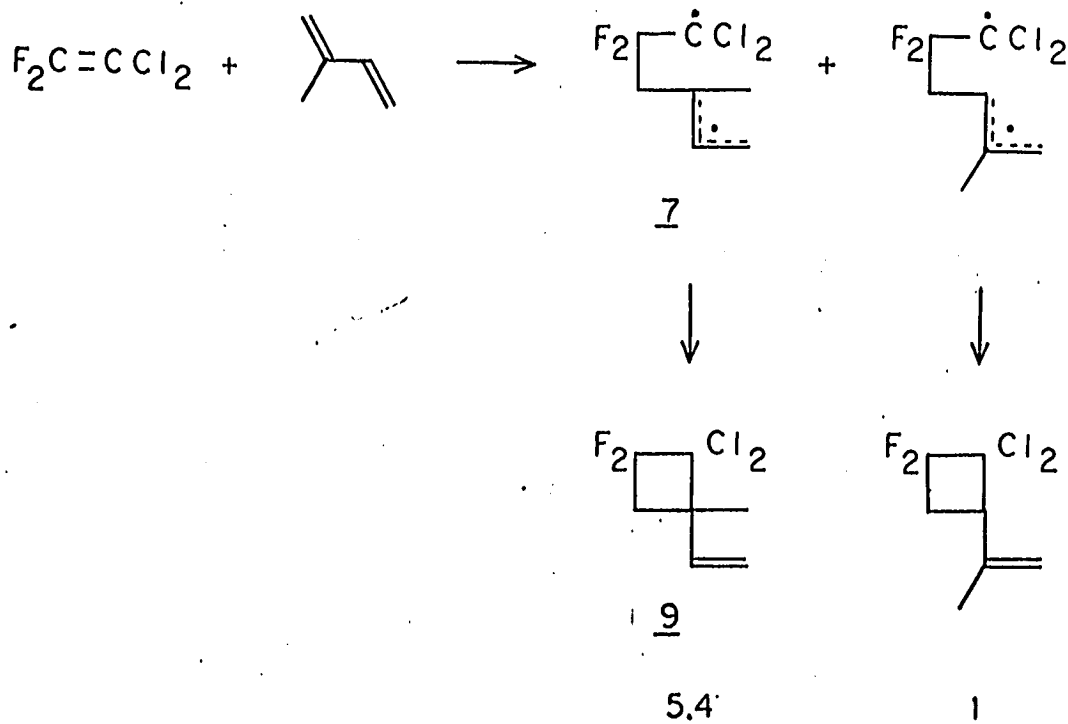
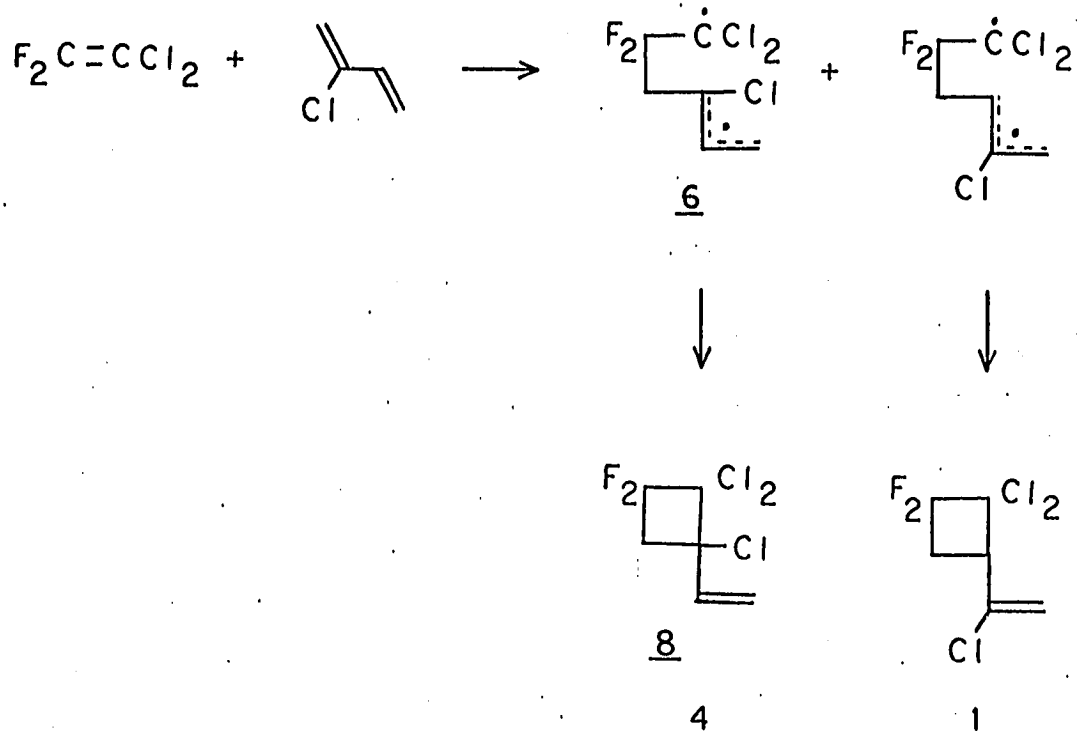
the observed 4.^{2a}

Similarly cycloaddition of 1122 to dienes such as chloroprene and isoprene may be explained in terms of the most stable biradical intermediates 6 and 7 leading to major products 8 and 9.⁴ In fact substitution of methyl or chlorine in butadiene accelerates fluoroalkene cycloaddition only as long as these groups may contribute to the stabilization of the biradical intermediate. Otherwise they decelerate cycloaddition. For example, in butadienes 1-methyl decelerates 1,2-cycloaddition but accelerates 3,4-cycloaddition whereas 2-methyl accelerates 1,2-cycloaddition but decelerates 3,4-cycloaddition.⁵ This is in contrast to the Diels-Alder reaction, a one-step concerted cycloaddition, in which substitution of methyl at the reactive centers (e. g. trans-piperylene with maleic anhydride) causes acceleration.⁵ More important though, nearly equivalent acceleration by resonance stabilization of the intermediate is observed in the cycloadditions of chloroprene and isoprene to 1122 in spite of the opposing polarities of chlorine and methyl.⁵ This again is in contrast to the corresponding Diels-Alder reaction with maleic anhydride which is accelerated by electron donating methyl but decelerated by electron withdrawing chlorine.⁵

Only in one case have dipolar effects perhaps significantly influenced the course of a fluoroalkene cycloaddition. Bartlett and

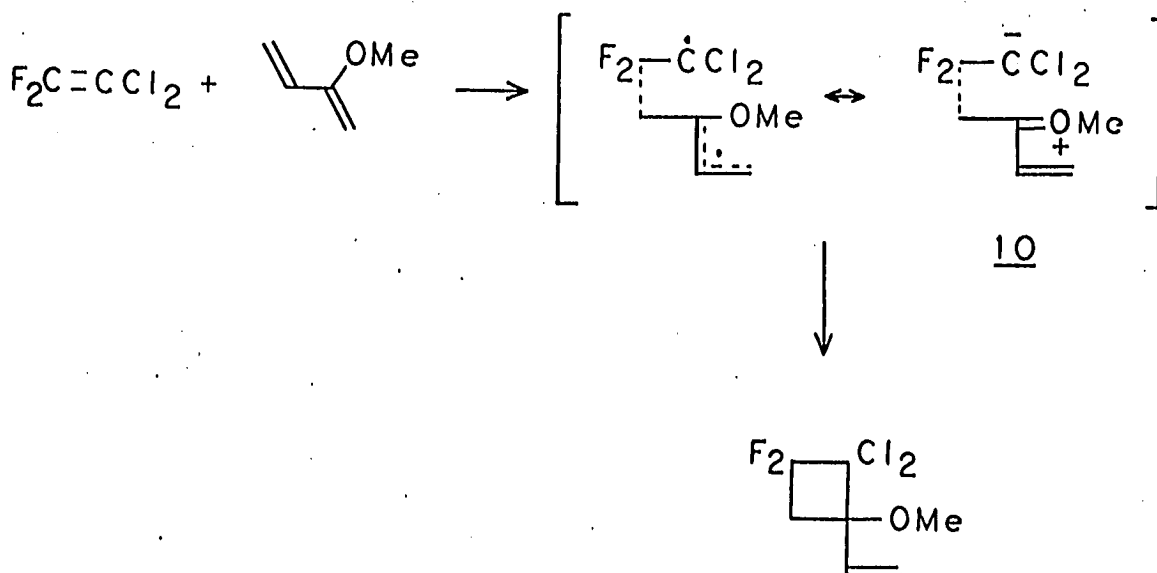
4. P. D. Bartlett, L. K. Montgomery, and B. Seidel, J. Am. Chem. Soc., 86, 616(1964).

5. P. D. Bartlett and L. K. Montgomery, J. Am. Chem. Soc., 86, 628(1964).



4

coworkers have found that 2-methoxybutadiene cycloadds better than 50:1 1,2 relative to 3,4. Inasmuch as methoxy cannot stabilize a radical center by d orbital effects as does chlorine or by hyperconjugative effects as does methyl, the exceptional degree of orientation probably results from dipolar contributions in the transition state 10.⁶



This is hardly to say that overlap between fluoroalkene cycloaddition and two-step dipolar cycloaddition is a serious consideration.

Fluoroalkenes normally add alkenes with no particular substituent polarity effects (see above), no particular solvent polarity effects,⁷

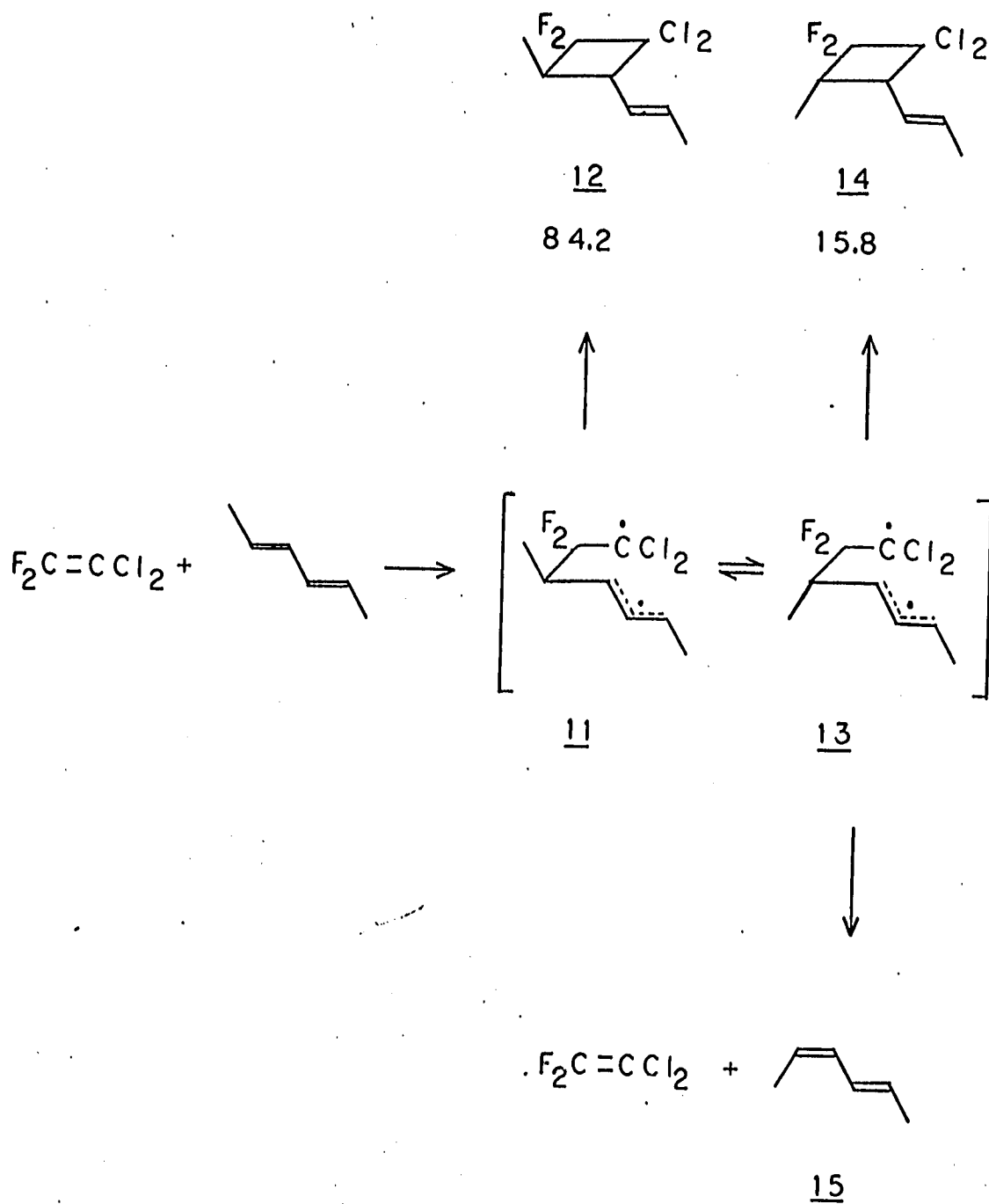
6. P. D. Bartlett, G. E. H. Wallbillich, and L. K. Montgomery, *J. Org. Chem.*, 32, 1290(1967).

7. The rate of (2+2) cycloaddition of 1122 to butadiene is three times as great in methanol or nitromethane as in hexane. J. S. Swenton, unpublished results cited in: P. D. Bartlett and K. E. Schueller, *J. Am. Chem. Soc.*, 90, 6071(1968).

and considerable free rotation leading to loss of configuration (see below). Dipolar (2+2) cycloadditions generally involving cyanoethylenes contrast sharply in behavior. For example, the rate of cycloaddition of TCNE to p-methoxystyrene increases 10^5 times on going from cyclohexane to nitromethane.⁸ In the cycloaddition of TCNE to substituted styrenes Hammett ρ values greater than -7 have been fitted to σ^+ .⁹ Quite frequently such dipolar cycloadditions show no rotation at all or solvent dependent rotation with loss of configuration.^{9, 10}

The presence of distinct biradical intermediates in fluoroalkene cycloadditions have been elegantly established by Bartlett and coworkers in their study of the cycloaddition of 1122 to the three isomers of 2,4-hexadiene.¹¹ Cycloaddition of 1122 to trans, trans-2,4-hexadiene, for example, produces an initial biradical intermediate 11 that may either close to adduct 12 or else rotate to a new biradical intermediate 13 before subsequent closure to 14. Similar results were obtained with the cis, trans- and cis, cis-2,4-hexadiene isomers. Consistent

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8. Unpublished results of D. W. Wiley cited in ref. 9. See also: J. K. Williams, D. W. Wiley, and B. C. McKusick, J. Am. Chem. Soc., 84, 2210(1962).
9. B. D. Kramer, Ph. D. Thesis, Harvard University, 1968.
10. a/ C. J. Dempster, Ph. D. Thesis, Harvard University, 1968.
b/ S. Proskow, H. E. Simmons, and T. L. Cairns, J. Am. Chem. Soc., 88, 5254(1966).
11. L. K. Montgomery, K. Schueller, and P. D. Bartlett, J. Am. Chem. Soc., 86, 622(1964).



with this mechanism is the recent observation that biradical ¹³ undergoes β -scission to isomerized 2,4-hexadiene ¹⁵ with a cis double bond in the place of the original trans.¹² A similar reversal of biradical formation has been noted in the cycloaddition of 1,1,2,2 to all three 1,4-dichlorobutadiene isomers¹³ but not in the cycloaddition of tetrafluoroethylene to trans, trans-2,4-hexadiene, presumably as a result of extreme C=C destabilization in tetrafluoroethylene.¹² The ability of difluoromethylenefluorene to isomerize 2,4-hexadienes has been attributed to entirely reversible biradical formation.¹⁴

In summary considerable evidence including orientation in products, absence of major solvent effects, and greater loss of configuration in cycloadducts than in recovered diene suggests that fluoroalkene (2+2) cycloaddition proceeds by reversible biradical formation followed by closure. It is only fair to point out, however, that there is no direct evidence for the biradical intermediate even to the extent of trapping. Attempts to actually observe biradicals in low temperature esr (although not generated by a cycloaddition path) have apparently failed for singlet biradicals¹⁵ but have succeeded for species

12. P. D. Bartlett, C. J. Dempster, L. K. Montgomery, K. E. Schueller, and G. E. H. Wallbillich, J. Am. Chem. Soc., 91, 405(1969).

13. P. D. Bartlett and G. E. H. Wallbillich, J. Am. Chem. Soc., 91, 409(1969).

14. P. D. Bartlett, Science, 159, 833(1968).

15. H.-D. Brauer, H. Stieger, J. S. Hyde, L. D. Kispert, and G. R. Luckhurst, Mol. Physics, 17, 457(1969).

resembling triplet biradicals.^{16, 17} Finally it is interesting to note that since the lifetime of a biradical in a normal cycloaddition reaction is on the order of that of a molecular rotation,¹¹ the situation is not far removed from the border between a well defined intermediate and the transition state for a direct reaction.¹⁸

2. Thermal (2+4) cycloaddition -- Diels-Alder cycloaddition: General reviews^{19a} as well as reviews emphasizing the aspects of mechanism,^{19b} substituent effects,^{19c} retro addition,^{19d} synthesis,^{19e} MO theory,^{19f} and stereochemistry^{19g} are readily available on the Diels-Alder reaction.

In respect to substituent and solvent effects, Diels-Alder (2+4) cycloaddition resembles the (2+2) biradical cycloaddition just described.

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16. G. L. Closs and L. R. Kaplan, J. Am. Chem. Soc., 91, 2168(1969).
17. P. Dowd, J. Am. Chem. Soc., 92, 1066(1970).
18. R. Wolfgang, Accounts Chem. Res., 3, 48(1970).
19. a/ R. Huisgen, R. Grashey, and J. Sauer, Chapt. 11: "Cycloaddition Reactions of Alkenes" in ed. S. Patai, The Chemistry of Alkenes, Interscience Publishers, New York, 1964. b/ J. Sauer, Angew. Chem. Internat. Ed. Eng., 6, 16(1967). c/ Y. A. Titov, Russian Chem. Review, English Translation, 31, 267(1962). d/ H. Kwart and K. King, Chem. Rev., 68, 415(1968). e/ J. Sauer, Angew. Chem. Internat. Ed. Eng., 5, 211(1966). f/ A. Streitwieser, Molecular Orbital Theory for Organic Chemists, John Wiley and Sons, Inc., New York, 1961, p. 432. g/ J. G. Martin and R. K. Hill, Chem. Rev., 61, 537(1961). These reviews cover a number of aspects of the Diels-Alder reaction (as, for example, secondary orbital effects) which are excluded in the following discussion because they are felt to have little bearing on the question of competing (2+2) and (2+4) cycloadditions.

First there are no major solvent effects;²⁰ for example, the rate of cyclopentadiene dimerization increases threefold on going from benzene to ethanol^{20a} and the rate of addition of cyclopentadiene to benzoquinone tenfold on going from n-hexane to ethanol.^{20b} In fact there is very little variation in rate even between vapor and solution phases indicating that dipolar contributions requiring solvation are minimal.²¹

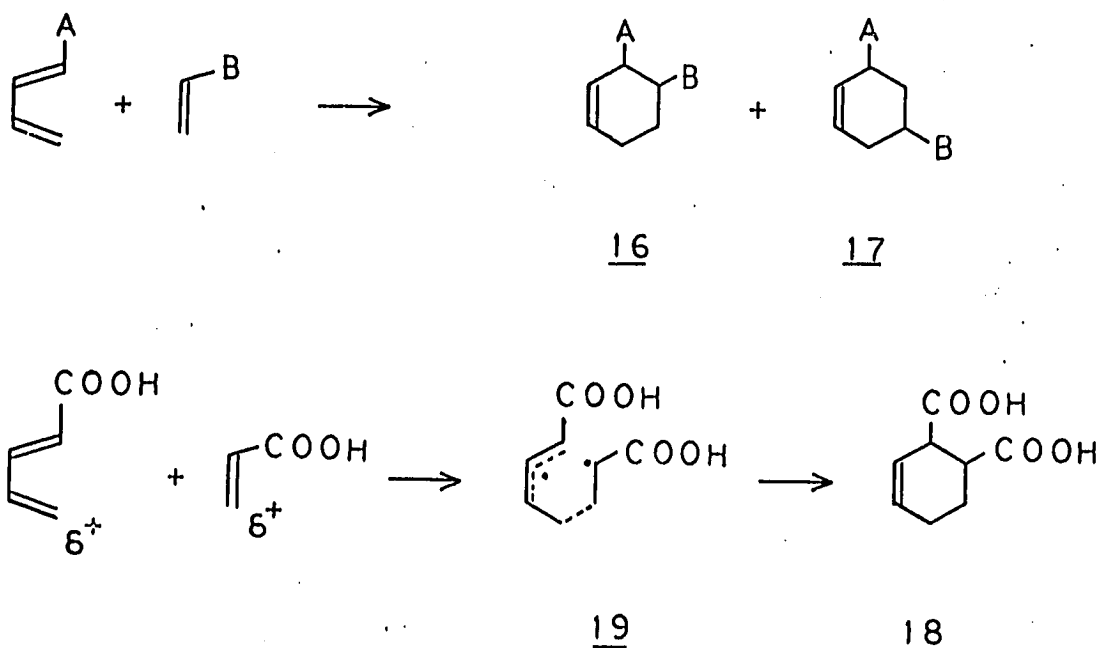
Studies of substituent effects in diene and dieneophile²² support the conclusion that dipolar species are not involved. A $\rho\sigma^+$ ($\rho = -0.6$ to -0.7) correlation has been found in the addition of maleic anhydride to 1-phenylbutadienes substituted in the phenyl group.^{22a, b} On the other hand a $\rho\sigma^-$ ($\rho = 0.29$) correlation has been found in the Diels-Alder addition of tetracyclone to methyl phenylpropiolates substituted in the phenyl group.^{22c, d} One might thus initially conclude

20. a/ H. Kaufmann and A. Wassermann, *J. Chem. Soc.*, 870(1939).
 b/ A. Wassermann, *J. Chem. Soc.*, 623(1942). c/ M. Ahmad and J. Hamer, *J. Org. Chem.*, 31, 2831(1966). d/ P. Brown and R. C. Cookson, *Tetrahedron*, 21, 1977(1965). e/ M. J. S. Dewar and R. Scott Pyron, *J. Am. Chem. Soc.*, 92, 3098(1970). e/ M. Gillois and P. Rumpf, *Bull. Soc. Chim. Fr.*, 1823(1959). Only reference citing significant and rather chaotic solvent effects. The failure to carry out product analyses, however, may account for apparent variations.
21. a/ A. Wassermann, *J. Chem. Soc.*, 1028(1936). b/ A. Wassermann, *Trans. Faraday Soc.*, 34, 128(1938).
22. a/ Y. Okamoto and H. C. Brown, *J. Org. Chem.*, 22, 485(1957).
 b/ E. J. DeWitt, C. T. Lester, and G. A. Ropp, *J. Am. Chem. Soc.*, 78, 2101(1956). c/ D. N. Mathews and E. I. Becker, *J. Org. Chem.*, 31, 1135(1966). d/ I. Benghiat and E. I. Becker, *J. Org. Chem.*, 23, 885(1958). e/ D. C. Ayres and J. R. Smith, *Chem. Commun.*, 886(1967).
 f/ A. Ahmad and J. Hamer, *J. Org. Chem.*, 31, 2329(1966). g/ C. M. Charton, *J. Org. Chem.*, 31, 3745(1966).

that dipolar effects are quite important since better fits are occasionally found for σ^{-+} and σ^{-} than for σ^{-} . However, in both additions cited, maleic anhydride to 1-phenylbutadienes and methyl phenylpropiolates to tetracyclone, there is still less than a tenfold rate difference between p-MeO and p-NO₂. In fact by way of comparison the purely free radical decomposition of substituted t-butyl phenylperacetates shows a similar $\rho\sigma^{-+}$ ($\rho = -1.20$) correlation with a 40 fold rate difference between p-MeO and p-NO₂. This behavior contrasts sharply with that of dipolar cycloadditions mentioned earlier.^{8, 9} The use of σ^{-+} for substituted dienes and σ^{-} for substituted dienophiles checks neatly with normally observed polarity effects wherein a relatively electron donating diene reacts most readily with an electron withdrawing dienophile.^{24, 25} Using an extended form of the Hammett equation, Charton has separated the inductive and resonance effects. He finds the resonance effect is sufficiently large that the transition state for Diels-Alder addition must involve remarkably little conversion of the sp² centers to sp³,^{22g} a point which will become central in later arguments.

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23. P. D. Bartlett and C. Rückhardt, J. Am. Chem. Soc., 82, 1756(1960).
24. a/ J. Sauer, H. Wiest, and A. Mielert, Chem. Ber., 97, 3183(1964).
 b/ J. Sauer, H. Wiest, and A. Mielert, Z. Naturforsch., 17a, 203(1962). c/ J. Sauer, D. Lang, and A. Mielert, Angew. Chem. Internat. Ed. Eng., 1, 268(1962).
25. For reversed electron demand: J. Sauer and H. Wiest, Angew. Chem. Internat. Ed. Eng., 1, 269(1962).

Directive effects likewise suggest the minimal influence of polarity effects.^{19c} Although there are a very few exceptions²⁶ it is generally true that the adduct between a 1-substituted butadiene and a monosubstituted ethylene has orientation as in 16 rather than as in 17. For example, butadiene 1-carboxylic acid cycloadds acrylic acid to give predominantly 18 in spite of opposing polarity effects.²⁷



Such orientation is most readily understood in terms of radical stabilization in 19 where 19 is either a contributing structure to

26. J. S. Meek, D. R. Wilgus, and J. R. Dann, J. Am. Chem. Soc., 82, 2566(1960).

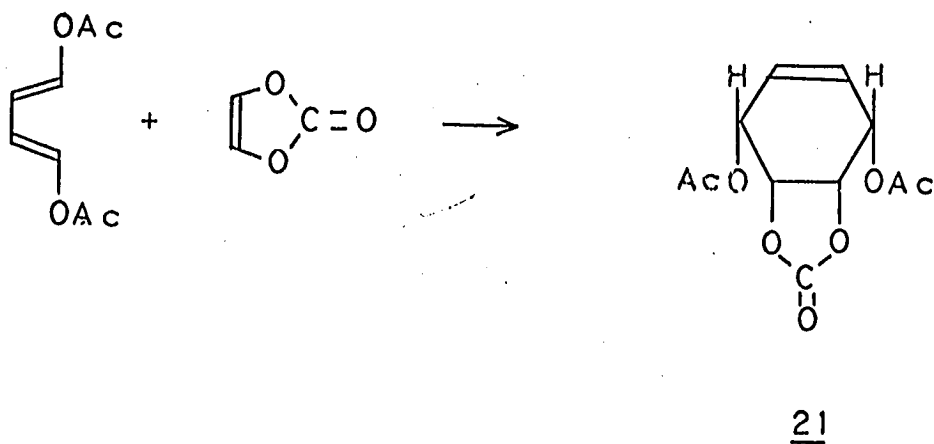
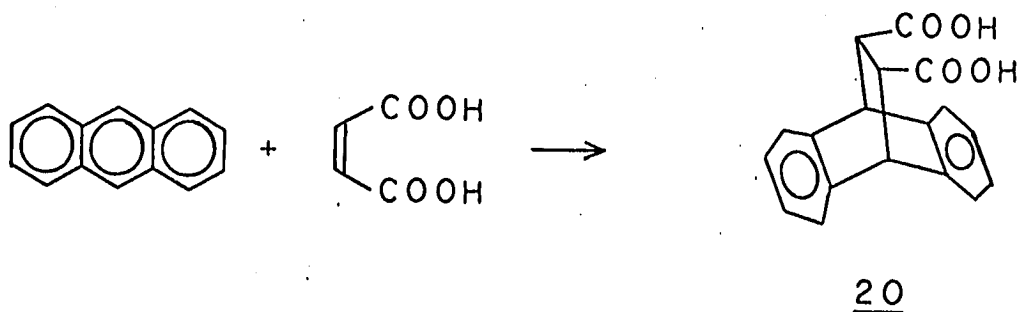
27. K. Alder and K. Heimbach, Chem. Ber., 86, 1312(1953).

the transition state or, less likely, the precursor to an actual biradical intermediate. Generally a decrease in the ratio of $\frac{16}{17}$ reflects considerable electrostatic repulsion, $A=B= -COO^-$,²⁷ or steric hindrance, $A= t\text{-butyl}$ and $B= -COOCH_3$.^{19c}

The solvent effects, substituent effects, and directive effects thus far mentioned are equally consistent with either a biradical two-center or a concerted four-center mode of cycloaddition. Presumably, the cyclic transition state for concerted cycloaddition will require great restriction of motion resulting in a low ΔS^\ddagger or A factor. Indeed for the Diels-Alder reaction ΔS^\ddagger is generally less than -30 e. u. and log A less than 6 -- both ΔS^\ddagger and A being rather constant so that rate variation derives largely from ΔH^\ddagger and E_a (see section II. A.).^{24, 25} Regrettably ΔS^\ddagger for biradical (2+2) cycloaddition is also found to be around -30 e. u.^{1, 28} so that a distinction on this basis is rather difficult. Comparison of calculated to experimental A factors for Diels-Alder addition generally favors a cyclic transition state^{29a-d} although assumption of a looser transition state for concerted addition leads to results consistent with an open biradical.^{29e}

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28. a/ B. Atkinson and A. B. Trenwith, J. Chem. Phys., 20, 754(1952).
 b/ B. Atkinson and A. B. Trenwith, J. Chem. Soc., 2082(1953).
 c/ J. Leitich, Angew. Chem. Internat. Ed. Eng., 8, 909(1969).
29. a/ A. Wassermann, J. Chem. Soc., 612(1942). b/ D. Rowley and H. Steiner, Discussions Faraday Soc., 10, 198(1951). c/ M. Uchiyama, T. Tomioka, and A. Amano, J. Phys. Chem., 68, 1878(1964).
 d/ K. E. Lewis and H. Steiner, J. Chem. Soc., 3080(1964). e/ G. B. Kistiakowsky and W. W. Ransom, J. Chem. Phys., 7, 725(1939).

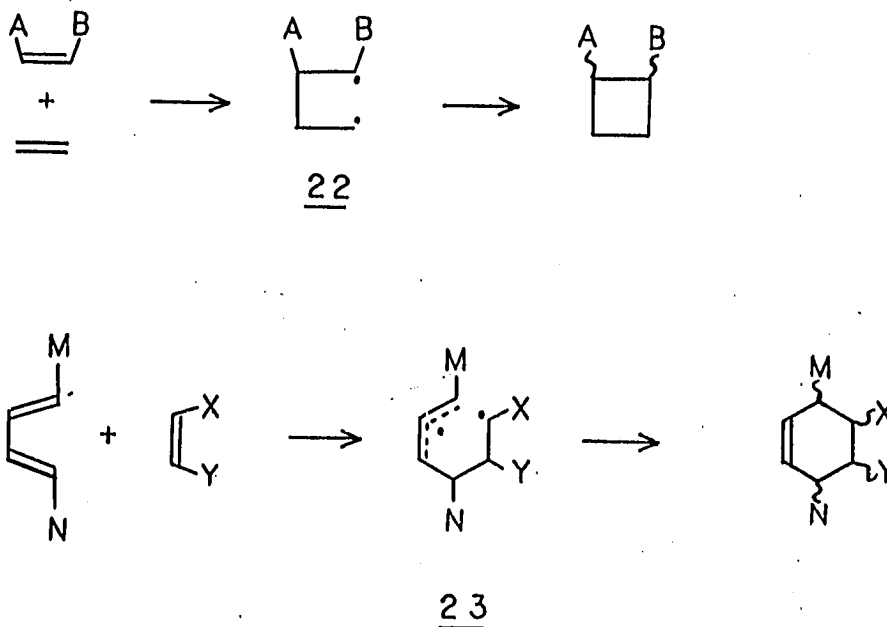
The Diels-Alder reaction distinguishes itself most effectively from biradical cycloaddition by its complete retention of configuration in both diene and dienophile.^{19g} For example, maleic acid adds to anthracene to give cis adduct 20,³⁰ and vinylidene carbonate cycloadds trans, trans-1,4-diacetoxybutadiene to give all cis adduct 21.³¹



30. W. E. Bachmann and L. B. Scott, J. Am. Chem. Soc., 70, 1458(1948).

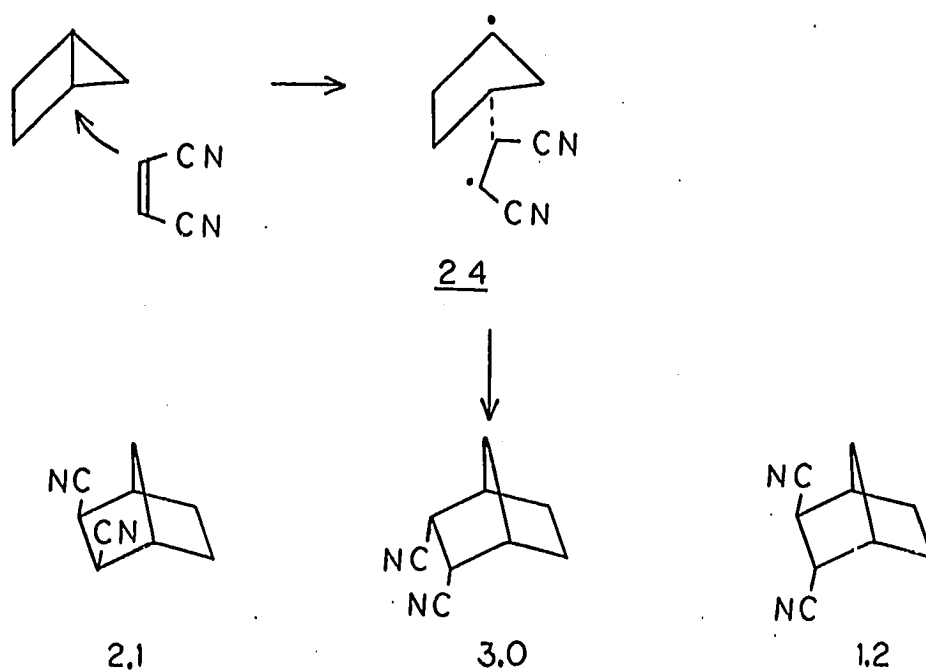
31. R. Criegee and P. Becher, Chem. Ber., 90, 2516(1957).

There is every reason to expect the retention of configuration in (2+4) cycloaddition to exclude a biradical mechanism. From earlier discussions it will be recalled that the biradical intermediate 22 in (2+2) cycloaddition invariably results in loss of configuration of A with respect to B. Thus, there would be no basis on which to expect the more extended biradical 23 corresponding to 1,4-cycloaddition not to show similar loss of configuration of M with respect to N and of X with respect to Y. In fact singlet biradicals in $2\sigma\pi + 2\sigma\pi$ cycloadditions analogous to 23 have been found to rotate quite freely before closure: the 10-20% loss of configuration of cis- and trans-1,2-dicyanoethylenes on cycloaddition to bicyclopentane³² compares to



32. P. G. Gassmann, K. T. Mansfield, and T. J. Murphy, J. Am. Chem. Soc., 91, 1684(1969).

15-75% loss of configuration observed on 1,2 biradical cycloaddition of 1,2 to 2,4-hexadienes.¹¹ Regrettably it is hard to estimate the lifetime of 24 relative to that of 23. The considerably greater stabilization by allyl in 23 than by cyano in 24^{2b} may make biradical 24 shorter-lived. On the other hand 24 can be formed only by end-on underside attack³² and thus may start in a considerably more extended conformation³³ than 23, possibly making the lifetime of 24 the longer.

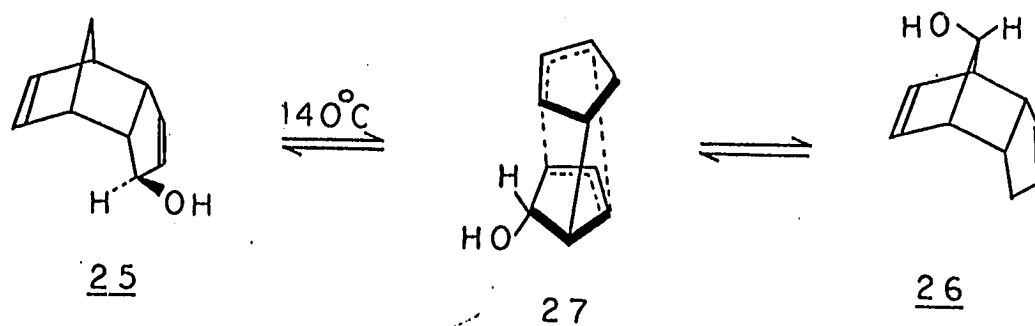


Largely on account of retention of configuration the Diels-Alder reaction is now considered to be a four-center concerted reaction in which both new bonds are formed simultaneously. Simultaneous bond formation is indeed allowed and predicted on the basis of the Woodward-

33. Unlike (2+2) addition through 22, (2+4) addition through 23 in a conformation suitable for immediate closure does not run into any orbital symmetry restriction (see ref. 34 and later discussion).

Hoffmann orbital symmetry rules for (2+4) cycloaddition in contrast to the (2+2) cycloadditions discussed previously (i. e. $\sigma\pi 2_s + \sigma\pi 2_s$).³⁴ These symmetry rules, however, have little to say about the relative rates of bond formation. If these rates were to become quite unequal, biradical character would arise naturally and conveniently rationalize the directive effects of substituents that occurs without any loss of configuration.³⁵

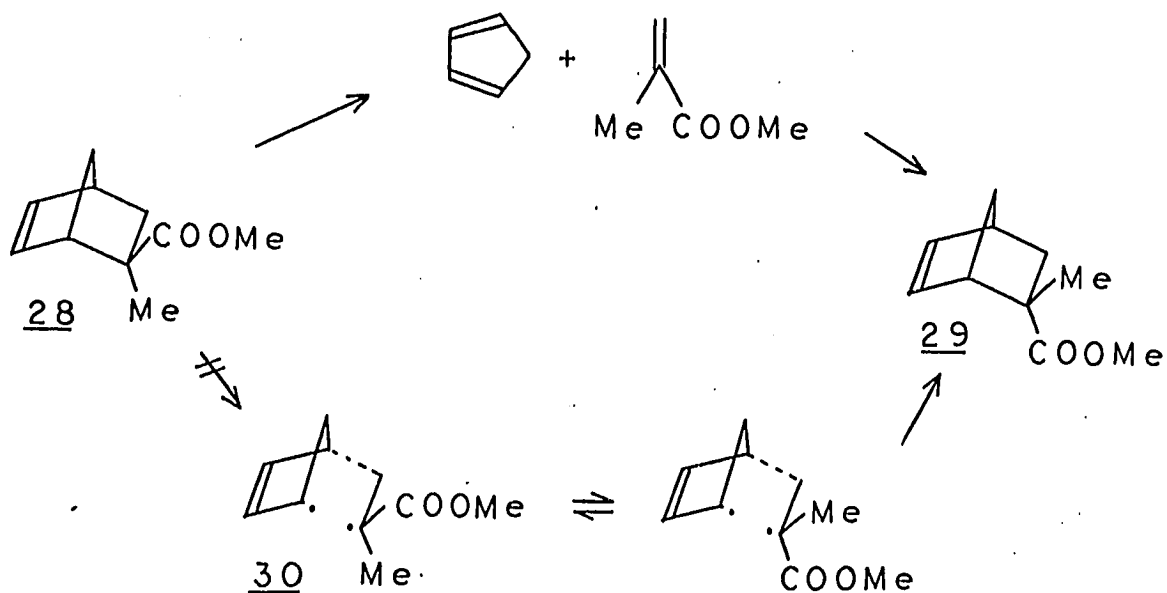
Unequal rates of bond formation was considered to be strongly implicated in the 140°C rearrangement of optically active 25 to its optically active isomer 26.^{35a} Heating 25 to temperatures still higher than 140°C initiates the retro Diels-Alder reaction, leading Woodward and Katz to hypothesize that 27, the intermediate involved in rearrangement of 25 to 26, is also on the reaction coordinate for Diels-Alder addition.



34. R. B. Woodward and R. Hoffmann, The Conservation of Orbital Symmetry, Verlag Chemie, GmbH, Weinheim/Bergstr., 1970

35. a/ R. B. Woodward and T. J. Katz, Tetrahedron, 5, 70(1959).
 b/ M. G. Ettliger and E. S. Lewis, Abstracts of Papers, 138th Meeting of the American Chemical Society, New York, N. Y., Sept. 11 to 16, 1960, p. 95P. c/ L. Salem, J. Am. Chem. Soc., 90, 553(1968).

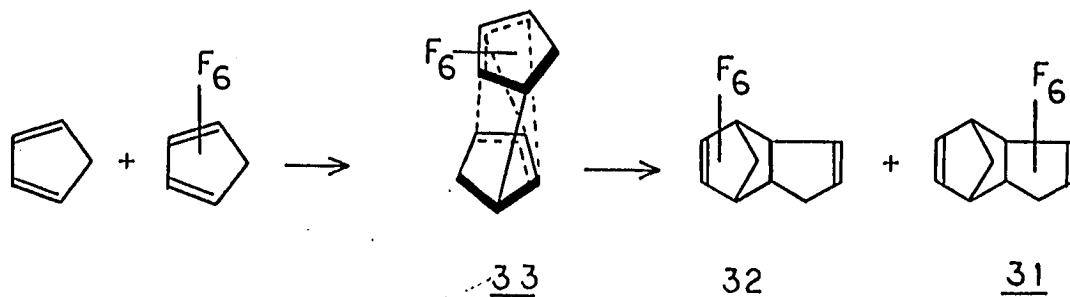
Similar rearrangements have been noted for other systems all of which are structurally related to 25 and 26 in that the two C=C and/or C=O bonds involved may approach each other much as in a dicyclopentadiene.³⁶ Indeed in those cases where a second double bond is not available evidence is lacking for the internal processes suggested by the Woodward-Katz treatment.^{19a, 37} For example, adduct 28 could isomerize to 29 by dissociation and recombination or, according to the Woodward-Katz scheme, by such unequal rates of bond dissociation as to give rise to an actual biradical intermediate 30



36. a/ R. P. Lutz and J. D. Roberts, *J. Am. Chem. Soc.*, **83**, 2198(1961).
 b/ P. Yates and P. Eaton, *Tetrahedron*, **12**, 13(1961). c/ E. Vogel and E.-G. Wyes, *Angew. Chem. Internat. Ed. Eng.*, **1**, 404(1962). d/ M. Livar, P. Kluchó, and M. Paldan, *Tetrahedron Lett.*, 141(1963). e/ R. C. Cookson, J. Hudec, and R. O. Williams, *Tetrahedron Lett.*, **22**, 29(1960).
37. a/ J. A. Berson and W. A. Mueller, *J. Am. Chem. Soc.*, **83**, 4940(1961).
 b/ J. A. Berson and A. Remanick, *J. Am. Chem. Soc.*, **83**, 4947(1961).
 c/ C. Ganter, U. Scheidegger, and J. D. Roberts, *J. Am. Chem. Soc.*, **87**, 2771(1965). d/ V. A. Mironov, T. M. Fadeeva, A. U. Stepaniantz, and A. A. Akhrem, *Tetrahedron Lett.*, 5823(1966).

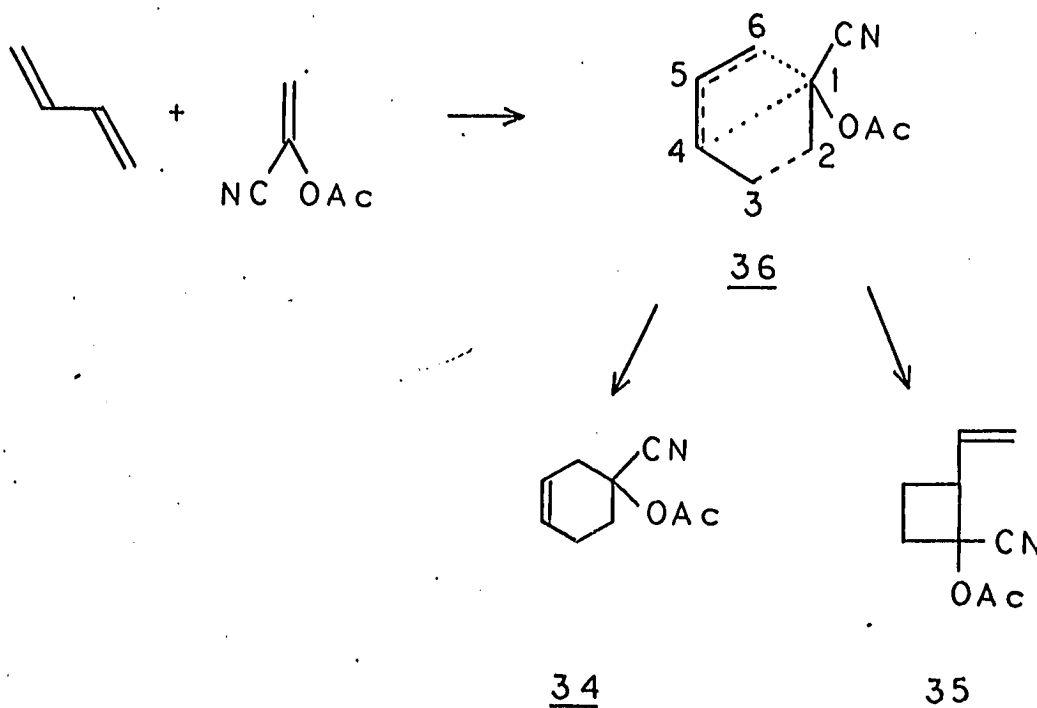
which rotates and then recloses. In spite of the considerable potential for radical stabilization in biradical 30 all optical activity originally in 28 was lost in forming 29, indicating the dissociation mechanism.^{37b} This prompted Berson to point out (1) that all rearrangements supporting the Woodward-Katz mechanism could equally well be interpreted as Cope rearrangements^{37b, 38} (an ambiguity that remains unresolved³⁹) and (2) that for those cases in which Cope rearrangement is inapplicable the Woodward-Katz mechanism most reasonably reduces to a one-step cycloaddition with different relative rates of bond formation.^{37b}

The Woodward-Katz approach has persisted in the treatment of competing modes of cycloaddition. Cyclopentadiene and perfluorocyclopentadiene give two adducts, 31 and 32, in essentially the same ratio independent of temperature and solvent.⁴⁰ This independence



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38. W. Von E. Doering and W. R. Roth, Angew. Chem. Internat. Ed. Eng., 2, 115(1963).
39. a/ C. Walling and J. Peisach, J. Am. Chem. Soc., 80, 5319(1958).
 b/ C. Walling and M. Naiman, J. Am. Chem. Soc., 84, 2628(1962).
 c/ S. W. Benson and J. A. Berson, J. Am. Chem. Soc., 84, 152(1962).
 d/ C. Walling and H. J. Schugar, J. Am. Chem. Soc., 85, 607(1963).
 e/ C. Walling and D. D. Tanner, J. Am. Chem. Soc., 85, 612(1963).
40. R. E. Banks, A. C. Harrison, and R. N. Haszeldine, Chem. Commun., 338(1966).

was interpreted as requiring a single Woodward-Katz transition state 33 which could collapse in either of two directions. Alternatively one could have two competing Diels-Alder reactions, (2+2) biradical competing with (2+4) concerted cycloaddition, or biradical (2+2) closure competing with (2+4) closure. All these possibilities might very well show little dramatic solvent or temperature dependence. A second such instance of competing cycloaddition is the formation of 34 and 35 on cycloaddition of α -acetoxyacrylonitrile to butadiene.⁴¹ The essential independence of rate and product distribution with respect to solvent over a 65°C temperature range was interpreted as requiring a single intermediate 36 that could break down to either 34 or 35.



41. J. C. Little, *J. Am. Chem. Soc.*, **87**, 4020(1965)

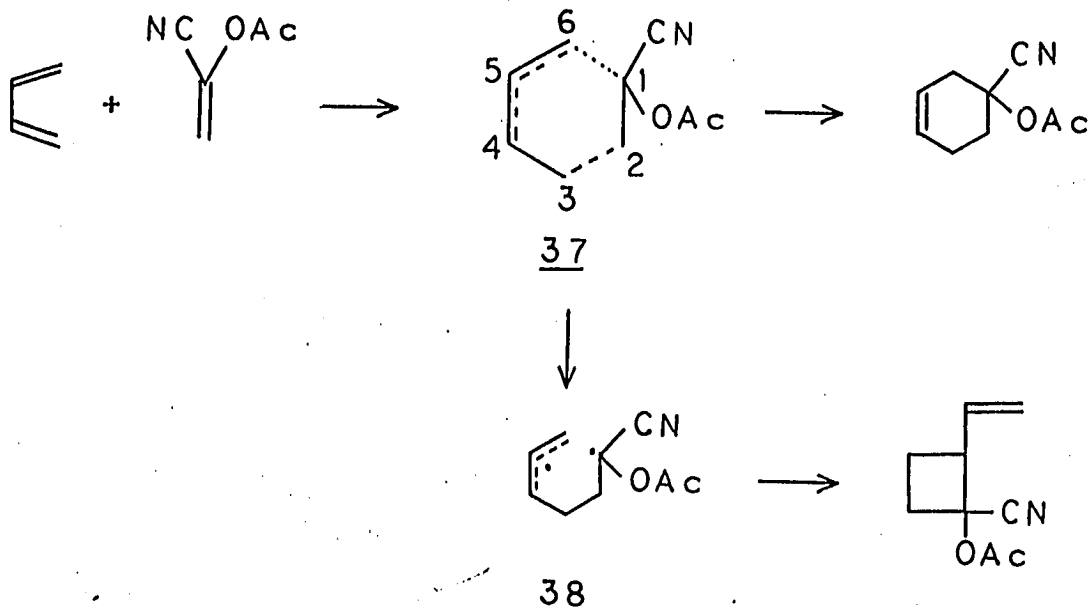
The Woodward-Katz hypothesis was adapted by including a primary bonding between C₂-C₃ and a secondary (less developed) bonding between C₁-C₄ and C₁-C₆. Strengthening of C₁-C₄ with respect to C₁-C₆ would lead to adduct 35 whereas strengthening of C₁-C₆ with respect to C₁-C₄ would lead to adduct 34. Such a competition between closure to a cyclobutane or to a cyclohexene is, of course, the same as must be considered for the addition of many fluoroalkenes to conjugated 1,3-dienes.

3. Competition between (2+2) and (2+4) cycloaddition: Of the three models to be considered, one may be eliminated fairly readily. This model involves Little's adaptation of the Woodward-Katz mechanism. His proposal utilizing intermediate 36 was made before the advent of orbital symmetry rules.³⁴ These rules suggest that the attractive interaction between C₁-C₄ in 36 is in fact repulsive for the $\pi^2_s + \pi^2_s$ additions being considered here. Indeed all known non dipolar $\pi^2_s + \pi^2_s$ thermal cycloadditions appear to proceed by a two-step biradical mechanism rather than along the concerted path suggested by Little's intermediate 36. This includes not only the fluoroalkene cycloadditions discussed in the first section but also those of benzyne⁴² and strained olefins.^{28c, 43} There are, of course, variations on the Little

42. a/ M. Jones, Jr., and R. H. Levin, Tetrahedron Lett., 5593(1968).
 b/ H. H. Wasserman, A. J. Solodar, and L. S. Keller, Tetrahedron Lett., 5597(1968). c/ I. Tabushi, R. Oda, and K. Okazaki, Tetrahedron Lett., 3743(1968). d/ I. Tabushi, K. Okazaki, and R. Oda, Tetrahedron, 4401(1969).

43. P. G. Gassmann, H. P. Benecke, and T. J. Murphy, Tetrahedron Lett., 1649(1969).

mechanism. An initial rate-determining transition state 37 could, for example, either go on to a cyclohexene or else break down to a biradical that eventually closes to a vinyl cyclobutane. As Berson points out, if the secondary attractive force between C_1-C_6 is strong enough to maintain diene and dienophile configuration, it is actually a partial bond^{37b} in which event there is no reason to expect 37 to be diverted along another path to 38. Thus, neither Little's original scheme nor possible variations offer a satisfactory explanation.



Previous discussion has established that purely (2+2) fluoroalkene cycloaddition proceeds by a biradical mechanism whereas purely (2+4)

Diels-Alder cycloaddition proceeds by a one-step concerted mechanism. Even when (2+2) and (2+4) cycloaddition occur simultaneously, it seems quite reasonable to assume that each retains its own distinct mechanistic characteristics. Bartlett and Schueller have applied this reasoning to the cycloaddition of dienes to ethylene and α -acetoxyacrylonitrile.⁴⁴ A consequence of this model involving competing biradical and concerted modes of cycloaddition is that (2+2) adducts should form with loss of diene and dienophile configuration whereas (2+4) adducts should form with complete retention of configuration.

An entirely different approach leading to the same model is based on observations that high energy photosensitized cycloaddition of trifluoroethylene to cyclopentadiene produces a considerably lower 1,4/1,2 adduct ratio than does the corresponding thermal cycloaddition.⁴⁵ If one assumes that the triplet biradical intermediate arising on photosensitized cycloaddition will give essentially the same product distribution as the singlet biradical intermediate responsible for thermal (2+2) addition, then the considerable excess of 1,4 adducts on thermal addition over those on photosensitized addition can be accounted for only by an additional competing process-- concerted Diels-Alder cycloaddition. Singlet and triplet biradicals, however,

44. P. D. Bartlett and K. E. Schueller, J. Am. Chem. Soc., 90, 6071, 6077(1968).

45. P. D. Bartlett, Quart. Rev. (London),(1970).

may not be entirely comparable inasmuch as different degrees of internal rotation and reversion to alkenes have been clearly demonstrated (ref. 46 and the 1,2,1,2-cyclopentadiene results discussed later).

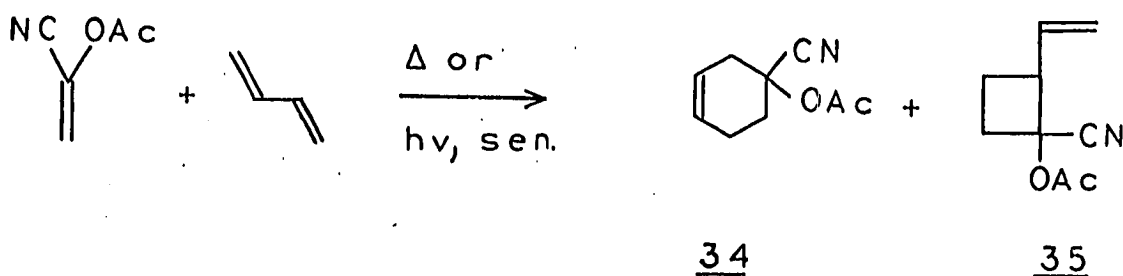
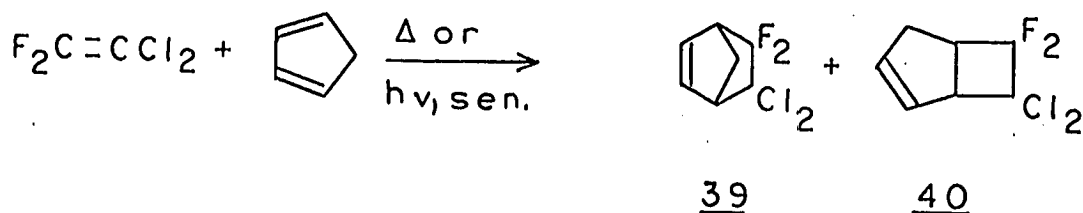
The third possible model requires diene and dienophile to form a single biradical that in turn closes either to a cyclohexene or to a vinylcyclobutane. One could consider this an example at the extreme end of the Woodward-Katz scale of unequal bond formation rates. This model was perhaps initially suggested by studies of the triplet photosensitized cycloaddition of dienes to dienophiles. Fluoroalkenes and acrylonitriles that thermally give 1,2-1,4 adduct mixtures quite frequently also give similar 1,2-1,4 adduct mixtures on photosensitized cycloaddition to dienes. For example, 1,1,2,2 cycloaddition of cyclopentadiene to give 39 and 40 in 5:1 ratio thermally and 1:2 ratio by photosensitization⁴⁷ and α -acetoxyacrylonitrile cycloaddition to butadiene to give 34 and 35 in 7:1 ratio thermally and variable ratio by photosensitization.⁴⁸ Even diene-dienophile systems that normally give only 1,4 addition thermally show simultaneous 1,2 and

46. P. D. Bartlett and N. A. Porter, J. Am. Chem. Soc., 90, 5317 (1968).

47. N. J. Turro and P. D. Bartlett, J. Org. Chem., 30, 1849(1965).

48. W. L. Dilling, R. D. Kroening, and J. C. Little, J. Am. Chem. Soc., 92, 928(1970).

1,4 cycloaddition with triplet photosensitization.⁴⁹ In such photosensitized cycloaddition with acyclic dienes the ratio of cyclobutane to cyclohexene adducts depends strongly on sensitizer energy.^{48, 50}



49. a/ W. L. Dilling, Chem. Rev., 69, 845(1969). b/ N. J. Turro and G. S. Hammond, J. Am. Chem. Soc., 84, 2841(1962). c/ G. S. Hammond, N. J. Turro, and R. S. H. Liu, J. Org. Chem., 28, 3297(1963). d/ D. Valentine, N. J. Turro, Jr., and G. S. Hammond, J. Am. Chem. Soc., 86, 5202(1964). e/ G. O. Schenck, S.-P. Mannsfield, G. S. Schomburg, and C. H. Krauch, Z. Naturforsch., 19b, 18(1964). f/ G. O. Schenck, J. Kuhls, and C. H. Krauch, Z. Naturforsch., 20b, 635(1965). g/ G. O. Schenck, J. Kuhls, and C. H. Krauch, Ann., 693, 20(1966). h/ P. D. Bartlett, R. Helgeson, and O. A. Wersel, Pure Appl. Chem., 16, 187(1968).

50. a/ G. S. Hammond, N. J. Turro, and A. Fisher, J. Am. Chem. Soc., 83, 4674(1961). b/ G. S. Hammond and R. S. H. Liu, J. Am. Chem. Soc., 85, 477(1963). c/ R. S. H. Liu, N. J. Turro, Jr., and G. S. Hammond, J. Am. Chem. Soc., 87, 3406(1965). d/ R. S. H. Liu and D. M. Gale, J. Am. Chem. Soc., 90, 1897(1968). e/ W. L. Dilling, J. Am. Chem. Soc., 89, 2742(1967). f/ W. L. Dilling and R. D. Kroening, Tetrahedron Lett., 5101, 5601(1968).

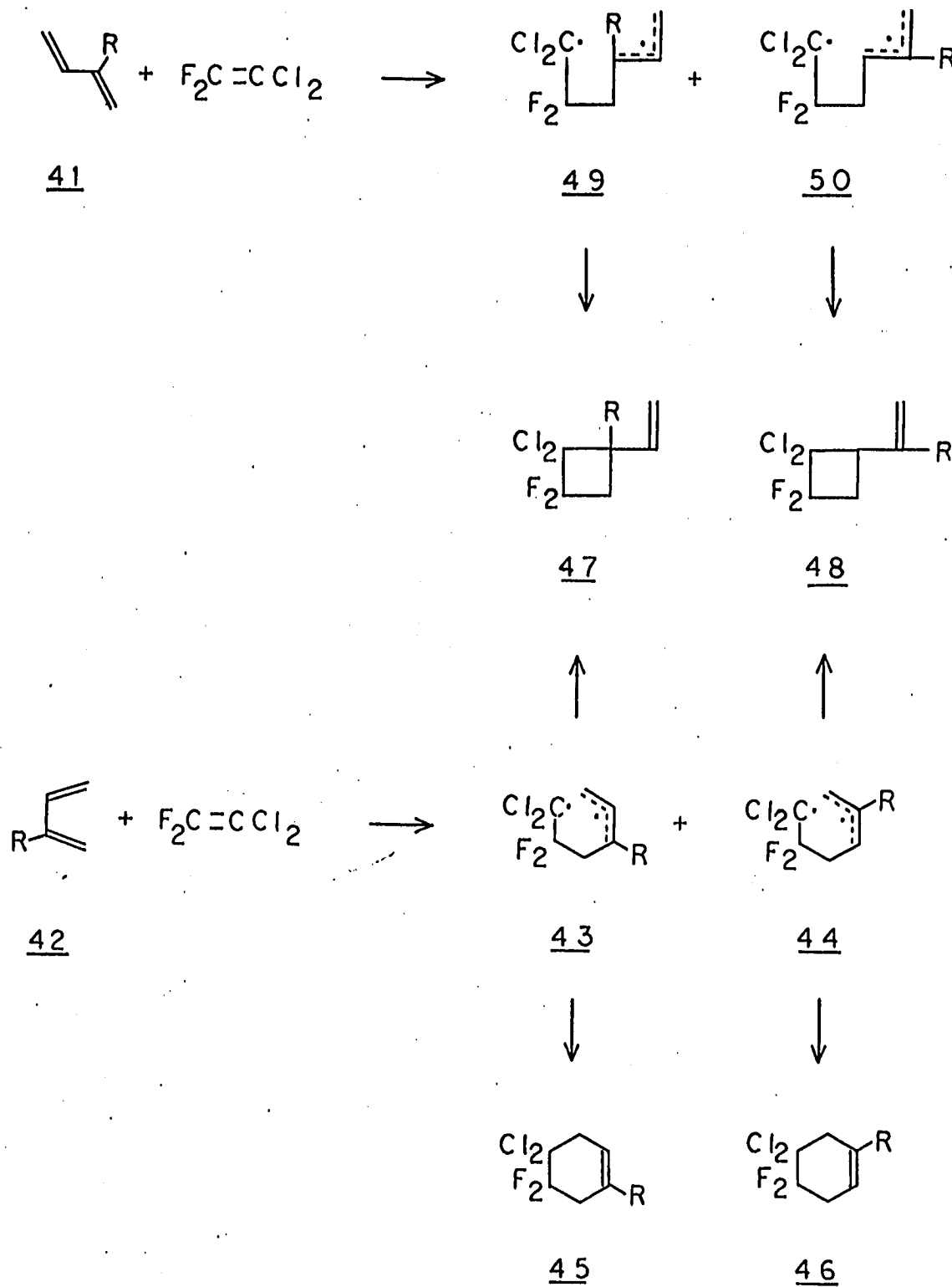
Presumably the relative efficiencies of excitation of s-cis and s-trans forms of a diene vary in a regular way with the sensitizer energy and s-trans excitation leads to a triplet biradical intermediate that may close only to vinylcyclobutanes whereas s-cis excitation leads to a triplet biradical intermediate that may close to cyclohexenes as well.

Bartlett and coworkers have shown that the cycloaddition of 1122 to 2-alkyl substituted butadienes bears a remarkable similarity to the photochemical results described above. A 2-alkyl butadiene may exist in either an s-trans 41 or an s-cis 42 conformation. Attack by 1122 on the s-cis diene 42 may give either of two biradicals 43 and 44. Closure of 43 and 44 will be partitioned between the far ends of the system giving cis-cyclohexenes 45 and 46 and the near ends of the system giving vinylcyclobutanes 47 and 48. Attack of 1122 on the s-trans diene gives biradicals 49 and 50 which may close only at the nearer ends forming vinylcyclobutanes 47 and 48. Attempts to close 49 and 50 at their more distant ends would give highly strained trans-cyclohexenes. As the size of the alkyl group increases the s-cis form of the butadiene will be increasingly favored so as to produce a larger percentage of biradicals with a chance of closing 1,4. In fact when R= methyl, one finds 1.6% 1,4 adduct and 98.4% 1,2 adduct but when R= t-butyl, 45% 1,4 adduct and 55% 1,2 adduct.⁵¹

51. P. D. Bartlett, G. E. H. Wallbillich, A. S. Wingrove, J. S. Swenton, L. K. Montgomery, and B. D. Kramer, J. Am. Chem. Soc., 90, 2049(1968).

Figure I

Influence of Diene Conformation on 1,2 vs. 1,4 Biradical Closure



If one locks the diene s-cis as in cyclopentadiene, one can still influence the 1,2/1,4 adduct ratio by controlling the distance separating the ends of the diene system. When the ends of the diene system are quite close and favorable to bridging as in cyclopentadiene, there results 80% 1,4 and 20% 1,2 adducts with 1122. The percent of 1,4 adduct drops off increasingly with separation between the ends of the s-cis diene system reaching less than 1% 1,4 adduct with 1,2-dimethylenecyclobutane.⁵²

Also consistent with the scheme in Figure I is the observation that the difference in activation energy, 2.3 Kcal/mole, between 1,2 and 1,4 adduct formation in the addition of 1122 to butadiene is roughly the difference in energy between s-cis and s-trans forms of the diene.⁵³

On the whole then thermal fluoroalkene cycloaddition possesses some remarkable similarities to photosensitized cycloaddition which is known to proceed through a triplet biradical intermediate. By implication fluoroalkene cycloaddition may also be biradical, albeit singlet rather than triplet. If this is the case, 1,2 competition with 1,4 measures the partitioning of a common and single biradical intermediate between 1,2 and 1,4 closure. Being

52. P. D. Bartlett, A. S. Wingrove, and R. Owyang, J. Am. Chem. Soc., 90, 6067(1968).

53. J. S. Swenton and P. D. Bartlett, J. Am. Chem. Soc., 90, 2055(1968).

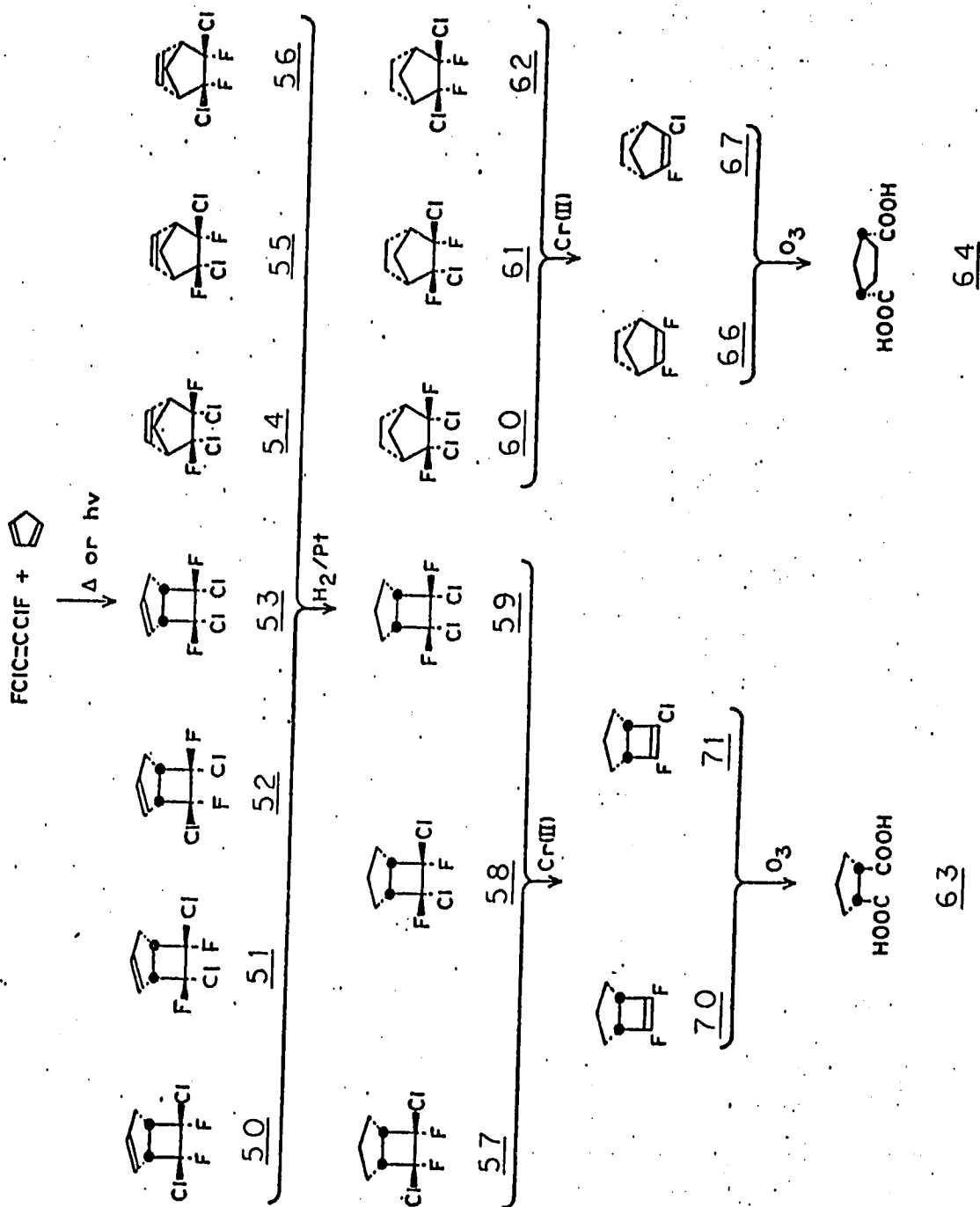
biradical, both diene and dienophile configuration would be lost not only in 1,2 but also in 1,4 adducts much as has been observed in photosensitized cycloaddition.^{9, 49h} The supporting arguments are, however, rather ambiguous: an s-cis diene conformation as well as a small separation between the ends of a diene system may be favoring 1,4 addition simply because of an increased ease of Diels-Alder addition^{51, 54} rather than any increased ease of 1,4 biradical closure.

⁵⁴. D. Craig, J. J. Shipman, and R. B. Fowler, J. Am. Chem. Soc., 83, 2885(1961).

B. Cycloaddition of 1,2-dichloro-1,2-difluoroethylene to cyclopentadiene

Competition between 1,2 and 1,4 cycloaddition of fluoroalkenes to dienes may arise from (1) partitioning a single biradical intermediate between 1,2 and 1,4 closure or (2) simultaneous biradical (2+2) and concerted (2+4) addition. Partitioning of a biradical intermediate should lead to loss of diene and dienophile configuration for both (2+2) and (2+4) adducts. In contrast competing biradical and concerted modes of cycloaddition should lead to (2+2) adducts with lost diene and dienophile configuration but to (2+4) adducts with completely retained configuration. Cycloaddition of 1,2-dichloro-1,2-difluoroethylene (hereafter designated 1212) to cyclopentadiene is the first system with the requisite stereochemistry for such configurational tests that also gives simultaneous (2+2) and (2+4) cycloaddition.

1. Separation of cross adducts: Heating cyclopentadiene with an excess of 1212 in a sealed Pyrex tube under nitrogen between 160 and 210°C affords all seven adducts, 50 to 56, theoretically expected. Final vpc separation of these adducts, however, is achieved only in their hydrogenated form, 57 to 62. Relative vpc retention times using 20% Carbowax 20M on Chromosorb P or W are, in the order of increasing retention,



63

64

before hydrogenation: 50, 51, 52, 53, 54 + 55, 56

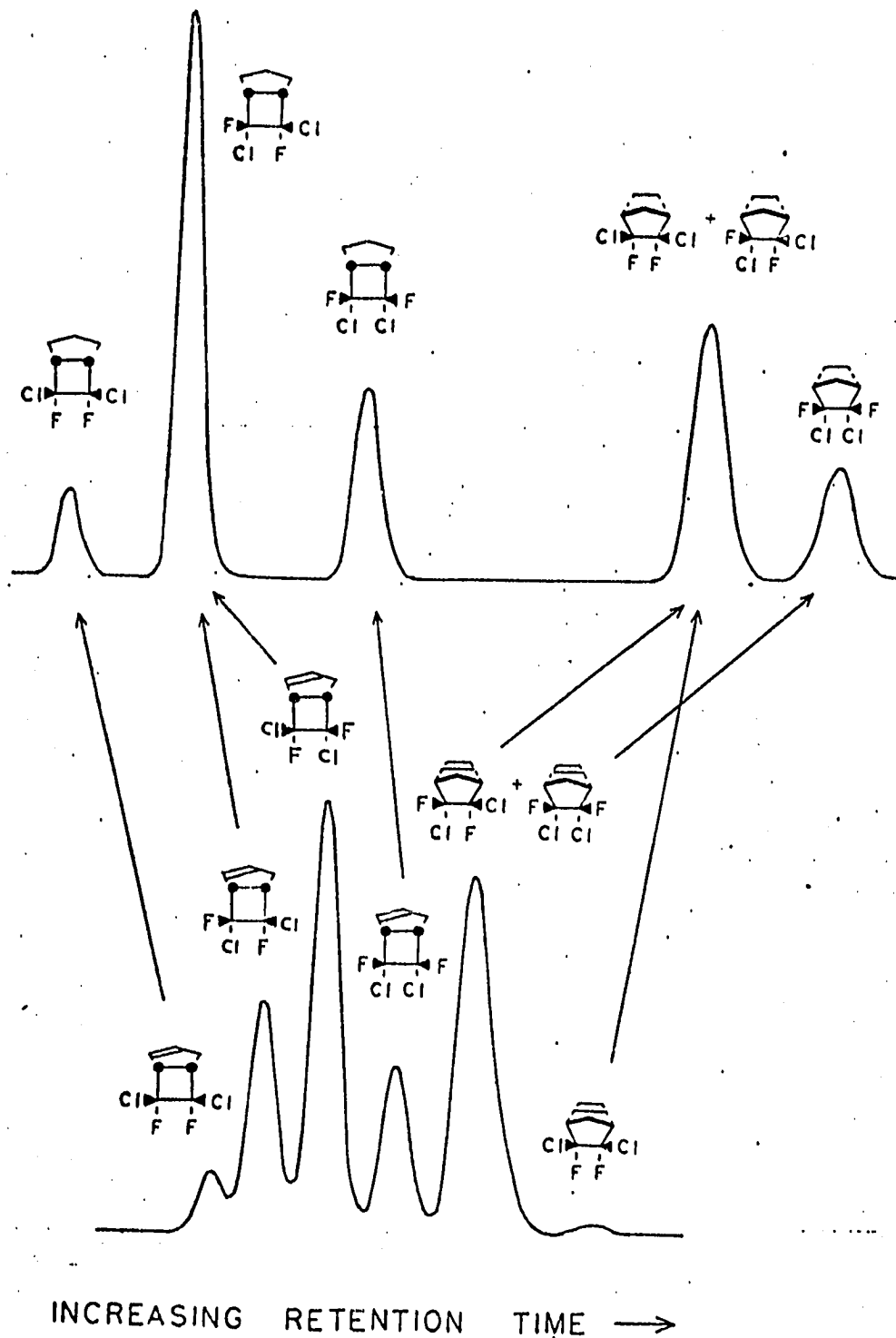
after hydrogenation : 57, 58, 59, 61 + 62, 60

Actual vpc traces are shown in Figure II. Clearly a superior separation is obtained after hydrogenation. Hydrogenated adducts 57, 58, 59, and 60 are immediately separable by preparative vpc. One must, however, return to the adduct mixture before hydrogenation in order to eventually obtain 61 and 62. Compound 56 may be separated by preparative vpc of the crude adduct mixture before hydrogenation. Separate hydrogenation of 56 then affords pure hydrogenated adduct 62. Preparative vpc of the adduct mixture before hydrogenation also affords a 54 + 55 mixture which may be separately hydrogenated to a 60 + 61 mixture. Preparative vpc of 60 + 61 affords pure 61 completing separation of the series of hydrogenated adducts 57 to 62. Hence it is the hydrogenated rather than the primary adducts before hydrogenation for which the structures will be proved. Working with the hydrogenated adducts does admittedly have the ultimate disadvantage that the distinction between the two trans 1,2 adducts 51 and 52 remains uncertain. More important though, inclusion of the hydrogenation step in no way hampers observation of cis and trans halogen configuration.

As will be described later, β -acetonaphthone photosensitized cycloaddition of 1212 to cyclopentadiene also produces the full seven adducts 50 to 56 which may be isolated in their hydrogenated form 57 to 62. These are shown to be identical to the thermal adducts

FIGURE II

CARBOWAX 20M VPC TRACES



by ^1H and ^{19}F nmr. It is actually from such photosensitized adduct mixtures that the vpc traces in Figure II were derived.

2. Confirmation of cross adduct structure: It must first be established that the products isolated by vpc are in fact cross adducts between 1212 and cyclopentadiene. Consistent with assignment of cross adduct structure is the observation that both thermal and photosensitized cycloaddition give the theoretically expected number of products both before and after hydrogenation and that these products are identical according to ^1H and ^{19}F nmr. Mass spectra give the correct parent peak masses and isotope ratios,

Adduct	(P+2)/P ^a	Parent Peak Mass ^b
<u>57</u>	0.66	199.9960
<u>58</u>	0.67	199.9965
<u>59</u>	0.65	199.9974
<u>60</u>	0.68	199.9971
<u>61</u>	0.67	199.9991
<u>62</u>	0.69	199.9974

a. calc. (P+2)/P = 0.65

b. calc. exact mass = 199.9971

The detailed mass spectral fragmentation patterns are reasonable but hardly revealing; for example, all hydrogenated adducts have peaks at mass 165 ($-\text{Cl}$) and mass 68 (C_5H_8^+). Proton nmr

spectra for 57 to 62 integrate for 6 bridge protons (methylene + ethylene for 1,4 adducts or trimethylene for 1,2 adducts) in the 1.3-2.5 δ region and 2 bridgehead protons in the 2.5-3.5 δ region. Fluorine-19 nmr spectra are eminently consistent with cross adduct structure and will be discussed in detail later.

3. Distinction between 1,2 and 1,4 hydrogenated adducts: The distinction between hydrogenated 1,2 and 1,4 adducts was made on the basis that chromous ion dehalogenation followed by ozonolysis gives cyclopentane cis-1,2-dicarboxylic acid 63 from 1,2 adducts in contrast to cyclopentane cis-1,3-dicarboxylic acid 64 from 1,4 adducts. This process is summarized on page 30.

The degradation to solely cis-cyclopentane dicarboxylic acids is consistent with the tacit assumption made until now that all the bicyclo(3.2.0)heptane 1,2 adducts are cis ring fused rather than trans ring fused. A trans ring fused bicyclo(3.2.0)hept-2-ene has been reported only for the adduct formed on photosensitization of the dichloromaleic anhydride-cyclopentadiene charge-transfer complex.⁵⁵ Such trans fused bicyclo(3.2.0)heptanes are otherwise entirely unprecedented. In the case of 1212-cyclopentadiene adducts no product instability or shifting product distributions were noted in the course of isolating 50 to 62. Furthermore the Zn-Cr(II)-ozonolysis method of degradation, that produced only cis dicarboxylic acids










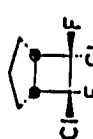
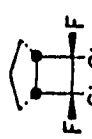
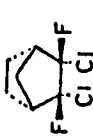
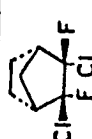

55. H.-D. Scharf, Tetrahedron Lett., 4231(1967).

from 1212-cyclopentadiene adducts, has proved to be entirely successful in detecting trans fused bicyclic systems in the case of adducts between 1212 or 1122 and trans-cyclooctene. There is every reason then to consider the assumption of cis fused 1,2 adducts a good one.

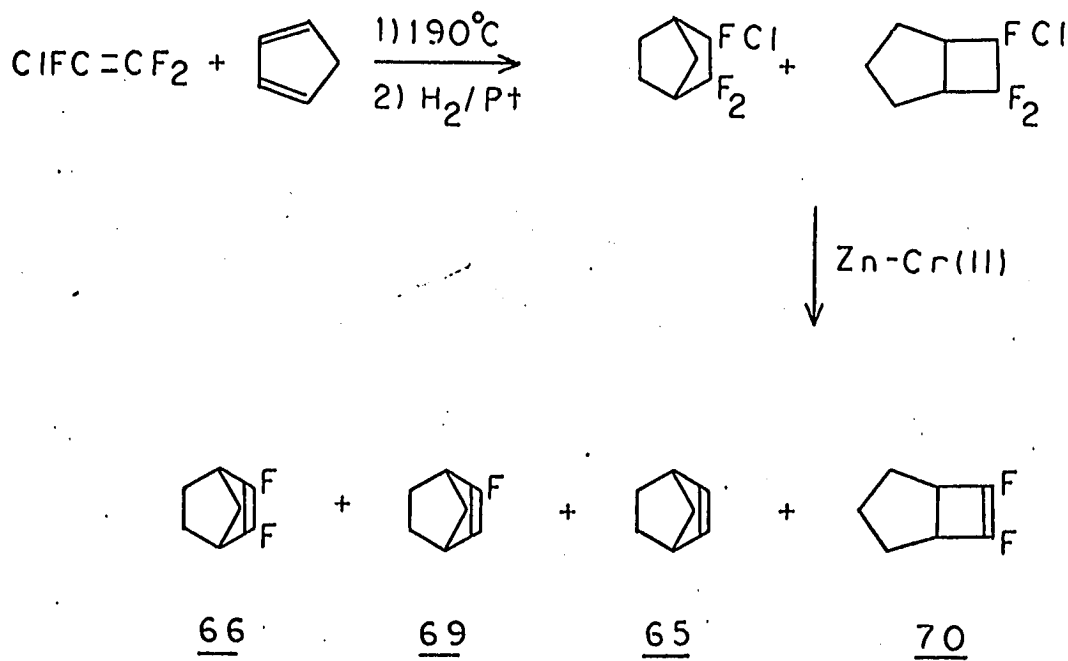
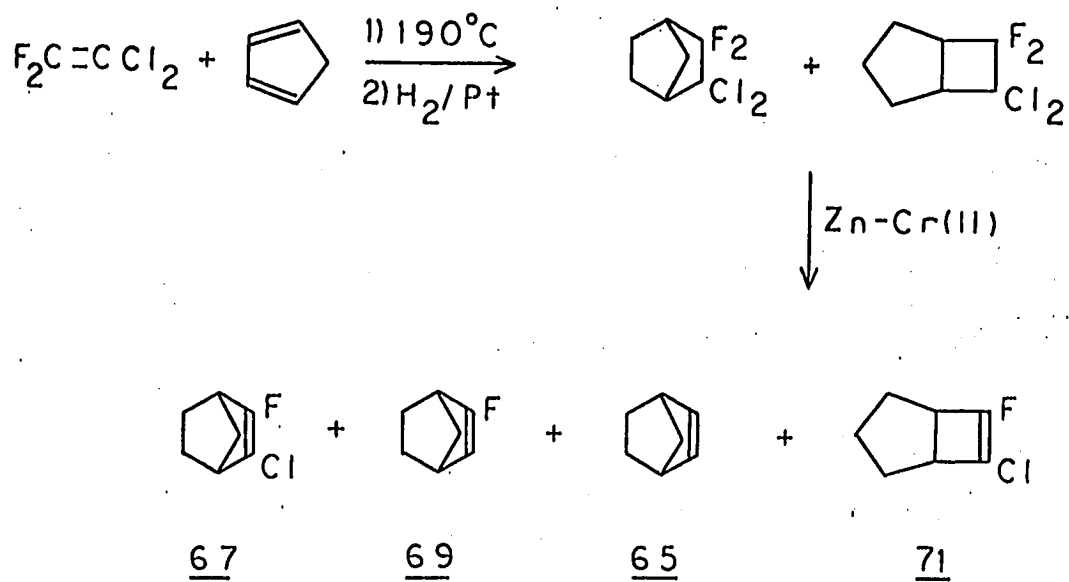
Since the hydrogenated adducts 57 to 62 were never isolated in sufficient quantity to allow product isolation from their individual Zn-Cr(II) dehalogenations, a less direct scheme was devised. The unseparated mixture of hydrogenated adducts 57 to 62 was dehalogenated by Zn-Cr(II) as a whole, the resulting mixture of products 65-72 then being separated by preparative vpc on 20% Carbowax 20M in sufficient quantity for ^1H , ^{19}F , and/or IR spectra. Then 25-33 mg samples of pure hydrogenated adducts 57-62 were separately dehalogenated by Zn-Cr(II). Product distributions were taken as the relative vpc trace areas of 65-72 under those conditions earlier found to afford their clean preparative vpc separation. The results are shown in Table I.

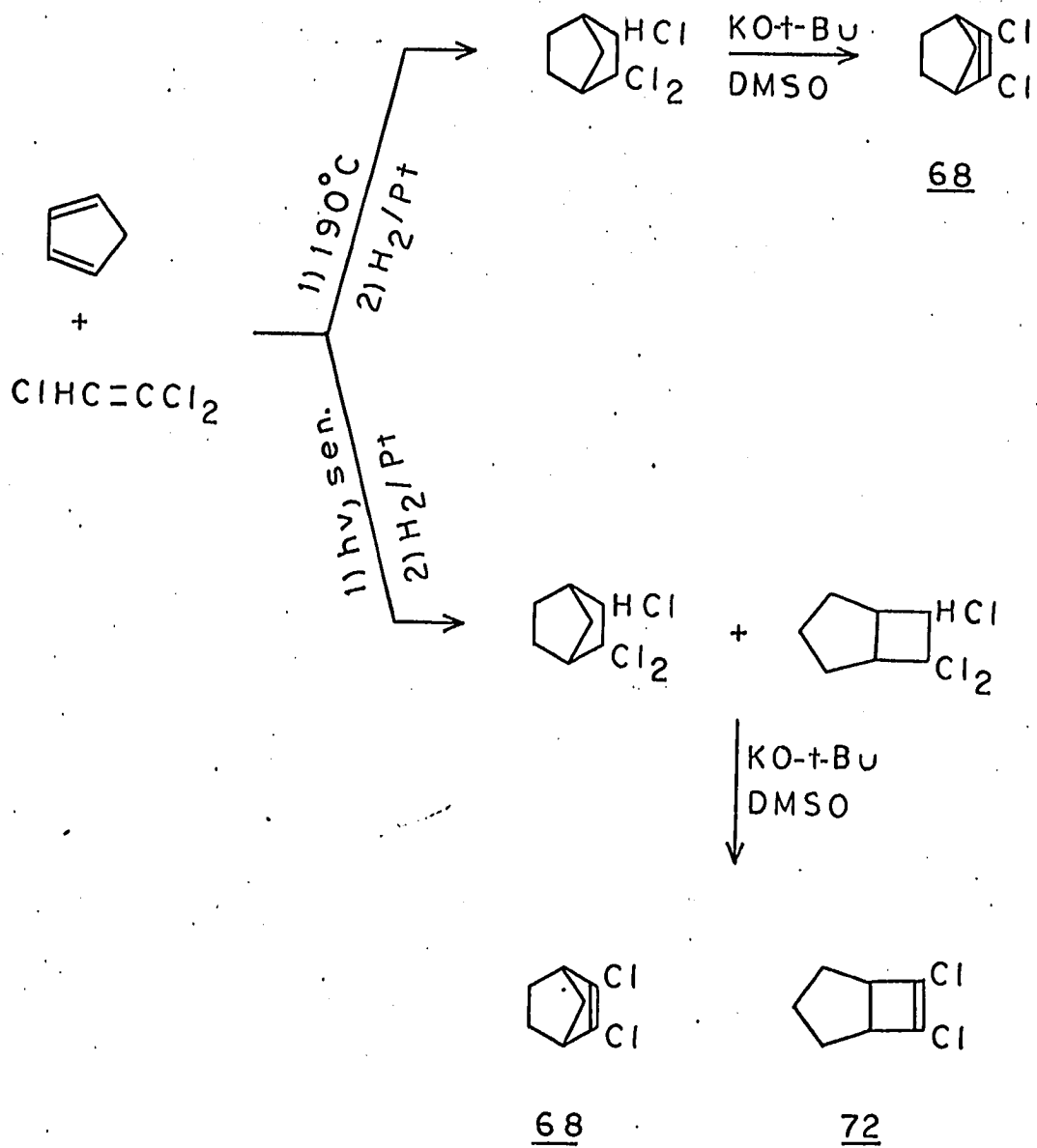
While norbornene, 65, is a well known compound, the remaining dehalogenation products 66-72 are new. Unfortunately the Zn-Cr(II) dehalogenation of the hydrogenated adducts 57-62 proved an impractical method of preparing sufficient quantities for full characterization by degradation. The following independent syntheses were employed,

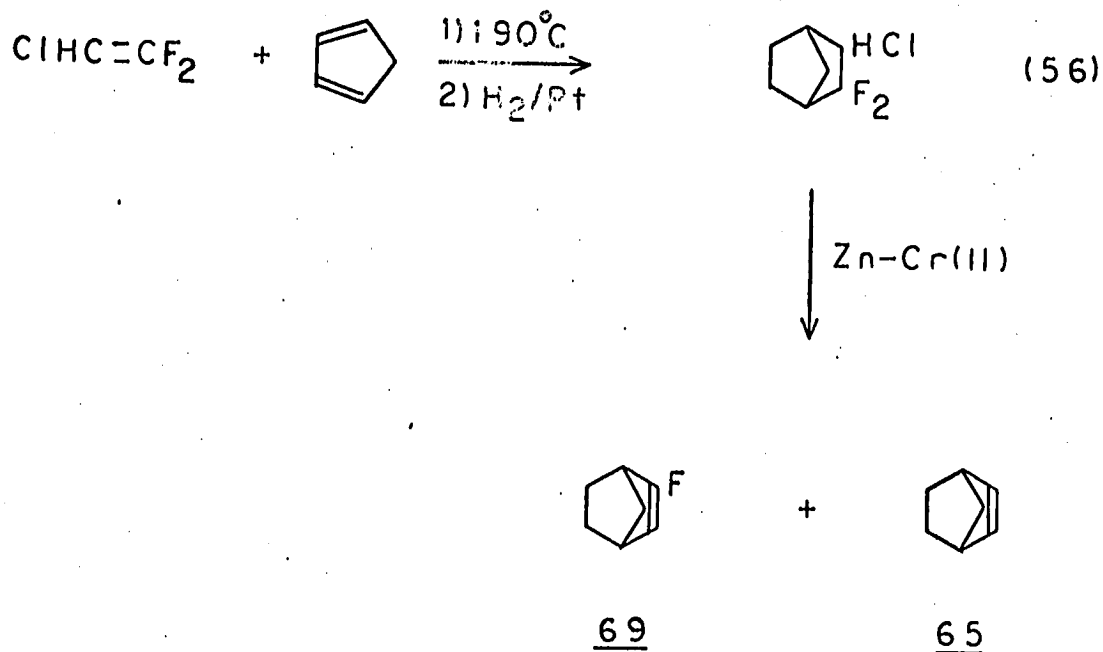
TABLE I

ADDUCT	UNCORRECTED VPC TRACE AREA OF PRODUCTS WITH Zn-Cr(III)									
	STARTING MATERIAL	 6.5	 6.6	 6.7	 6.8	 6.9	 7.0	 7.1	 7.2	UNKNOWN
	0.0	0.0	0.0	0.0	0.0	0.0	100.	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	76.7	15.3	0.0	9.0
	8.5	0.0	0.0	0.0	0.0	0.0	56.4	32.3	0.0	2.8
	49.5	3.8	13.4	32.3	0.0	0.5	0.0	0.0	0.0	0.0
	0.0	2.7	28.3	69.0	0.0	trace	0.0	0.0	0.0	0.0
	0.0	1.8	8.9	trace	0.0	9.3	0.0	0.0	0.0	0.0

*10M x 1/8", 20% carbowax 20M, 60/80W, F&M Scientific Model 700 vpc





















Since those syntheses starting with 1122 and chlorotrifluoroethylene involve considerable new material, they will be described more completely in later sections. On the other hand since those syntheses starting with trichloroethylene and 1-chloro-2,2-difluoroethylene are based chiefly on prior literature work,^{49h, 56} further discussion will be limited to the experimental section. The spectral and degradative evidence supporting structures 66-72 is collected in Table II.

56. B. Jacobson, unpublished results

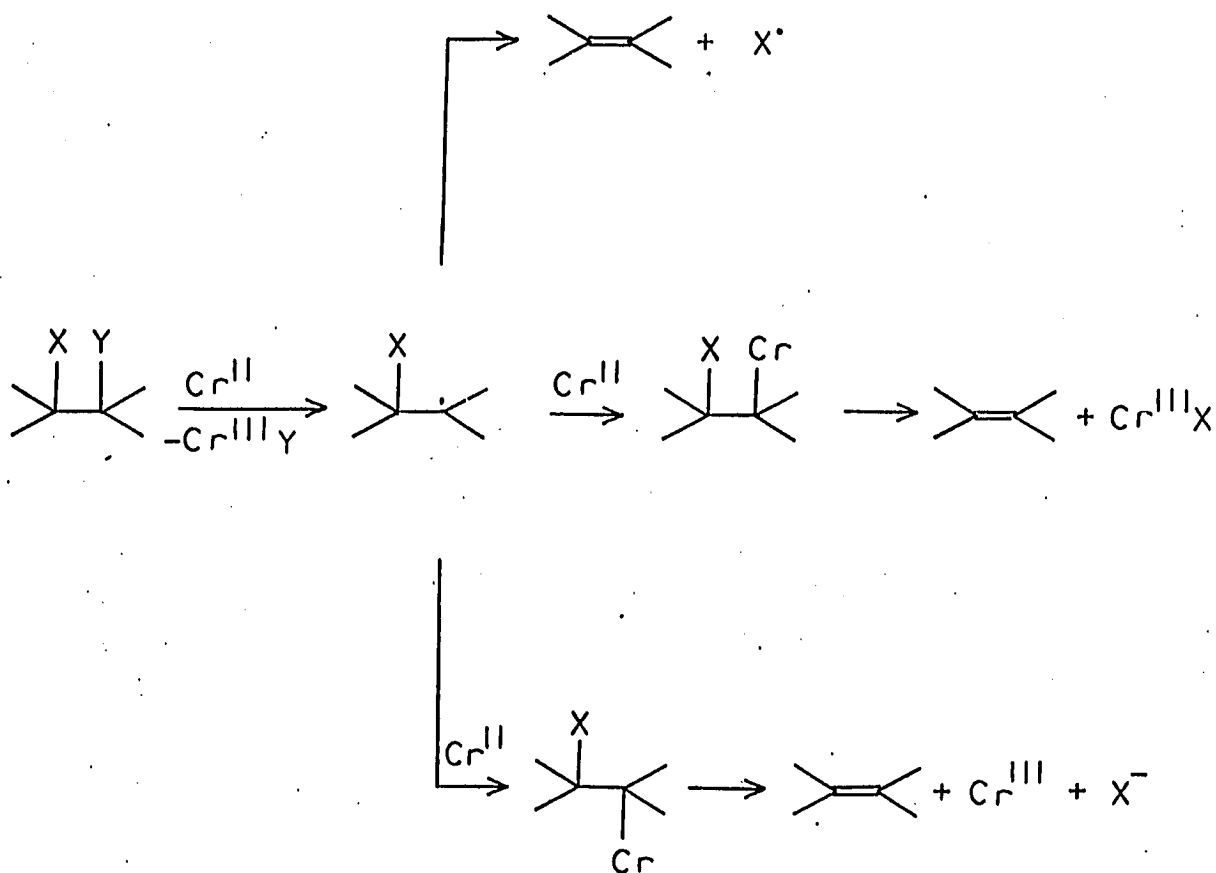
TABLE II
DATA SUPPORTING STRUCTURES 66-72

STRUCTURAL DATA	COMPOUND						
							
MELTING POINT OF OZONOLYSIS PRODUCT ^a	120-1°C	119-20°C	118-20°C		139-40°C	139-40°C	139-40°C
EXACT MASS OF PARENT PEAK: CALC. MASS: (P+2)/P RATIO (CALC.):	130.0546 130.0594	146.0240 146.0298 0.36 (0.33)	162.0003 161.9979 0.55 (0.55)	112.0682 112.0688	130.0546 130.0594	146.0313 146.0298 0.37 (0.33)	162.0003 151.9979 0.56 (0.55)
MAJOR FRAGMENT:							
VINYL/BRIDGEHEAD/BRIDGE PROTON INTEGRATION:	0.0/2.0/5.7	0.0/2.0/6.0	0.0/2.0/6.0	1.0/2.0/6.3	0.0/2.0/6.2	0.0/2.0/5.3	0.0/2.0/6.1
VINYL PROTON SPLITTING:				$J_{HF} = 3\text{hz}$			
FLUORINE-19 NMR SPECTRA:	SINGLET	SINGLET		SINGLET	DOUBLET	OCTET	
IR SPECTRA C=C STRETCHING: ^b	1710cm ⁻¹	1670cm ⁻¹	1630cm ⁻¹	1640cm ⁻¹	1760cm ⁻¹	1710cm ⁻¹	1640cm ⁻¹

a. Melting points of cyclopentane dicarboxylic acids: *cis*-1,3- (m=121°C); *cis*-1,2- (m=140°C); *trans*-1,3- (m=93.5°C); *trans*-1,2- (m=181°C).

b. W. Stuckey and J. Heicklen, *J. Am. Chem. Soc.*, **90**, 3952 (1968); perfluorocycloalkene Vc=c

4. Structural implications of Zn-Cr(II) dehalogenations: The dehalogenations of the hydrogenated adducts 57-62 were carried out by stirring a slurry of adduct, Zn dust, $\text{Cr}_2(\text{SO}_4)_3$, water, and dimethylformamide in a sealed tube under nitrogen at about $95-110^\circ\text{C}$. Under these conditions chromous ion is generated by the action of Zn on $\text{Cr}_2(\text{SO}_4)_3$. The reactive species is thus chromous ion although the dehalogenation can be demonstrated to proceed much more slowly with a somewhat different product distribution in the presence of zinc alone. Considerable work has been done on the Cr(II) dehalogenation

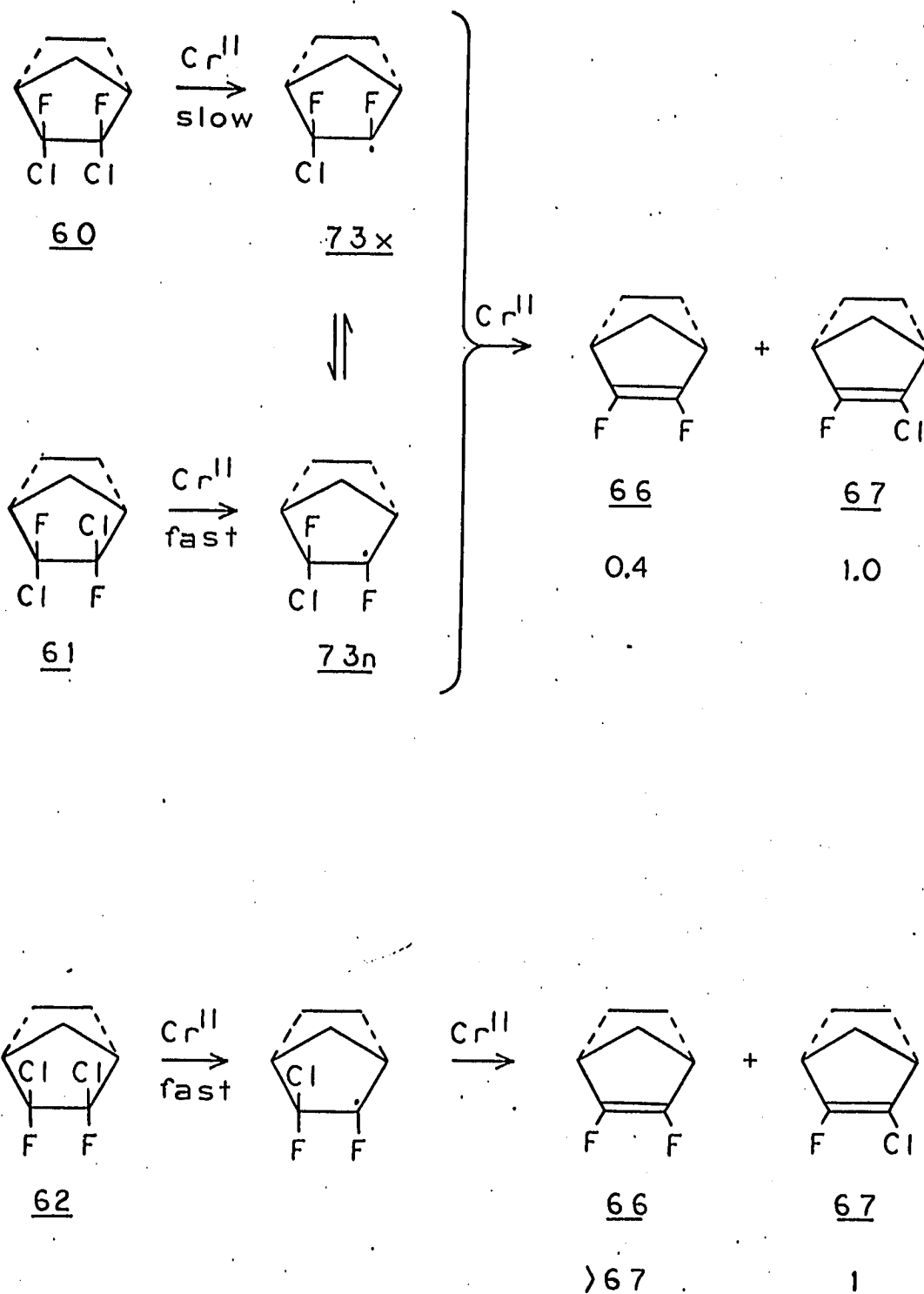


of alkyl halides and vicinal dihalides.⁵⁷ Vicinal dehalogenation is normally initiated by chromous ion abstraction of halogen to give a β -halo alkyl radical. This β -halo alkyl radical may either undergo immediate β -scission to an alkene or else form an alkyl chromium that readily decomposes in turn to an alkene. The ease of initial halogen abstraction is normally listed as $I > Br > Cl$ and by implication fluorine may not be abstracted initially at all. This scheme is applied to the hydrogenated 1,4 adducts 60-62 in Figure III. Adducts 61 and 62 with an exo chlorine available for abstraction apparently react much faster than 60 with no exo chlorine since roughly 50% of 60 remains unreacted under conditions that completely dehalogenate 61 and 62. This faster rate of reaction of exo chlorine adducts as well as the absence of 68 and 72 in the final products confirms the earlier suggestion that only chlorine is abstracted in the initial step. Although 60 and 61 react at very different rates, they apparently equilibrate to the same intermediate radical mixture 73x and 73n since they give essentially the same product distribution high in difluoroalkene 66. Although more convincing evidence is to be presented later such chromous ion arguments nonetheless can be used to assign halogen configuration tentatively to the hydrogenated adducts 57-62.

57. a/ J. R. Hanson and E. Premuzic, Angew. Chem. Internat. Ed. Eng., 7, 247(1968). b/ D. M. Singleton and J. K. Kochi, J. Am. Chem. Soc., 89, 6547(1967). c/ J. K. Kochi and D. M. Singleton, J. Am. Chem. Soc., 90, 1582(1968).

Figure III

Chromous Ion Dehalogenation of 1,4 Adducts



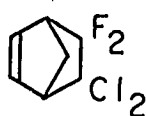
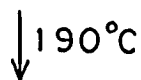
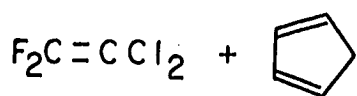
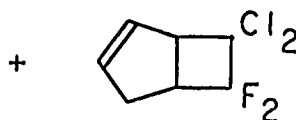
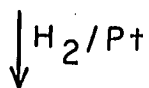
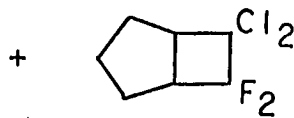
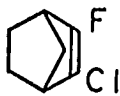
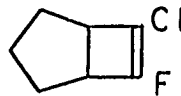
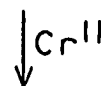
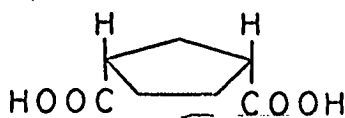
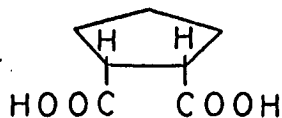
5. Cycloaddition of 1122 to cyclopentadiene: The cycloaddition of 1122 to cyclopentadiene is run at a higher temperature than previously reported.⁴ The use of 190°C virtually eliminates the cyclopentadiene dimers that accompany 74 and 75 at lower temperatures. A 20% Carbowax 20M column effects a clean separation of 74 and 75 allowing comparison to the nmr spectra of Montgomery.⁵⁸ All of the features in the nmr spectra of 74 and 75 prepared here are also present in Montgomery's spectra. Montgomery's nmr, however, have additional absorptions many of which quite obviously result from impurities.⁵⁸ One concludes that cycloaddition at higher temperatures has produced the desired adducts for the next step.

As far as synthesis is concerned the real interest lies in the hydrogenated adducts 76 and 77. Hydrogenation of the crude 74 + 75 mixture available from cycloaddition produces two products preparatively separable on a 20% DIDP vpc column. The proton nmr and mass spectral data are consistent with the assigned structures:

	<u>76</u>	<u>77</u>
Mass Spectrum		
1. Exact Mass ^a	199.9971	199.9965
2. (P+2)/P Ratio ^b	0.67	0.65
¹ H Nmr Integration		
3. Bridgehead/Bridge Ratio	2.0/6.0	2.0/6.0
a. calc. 199.9971	b. calc. 0.65	

Peaks in the mass spectra at mass 165 (-Cl) and mass 68 (C₅H₈⁺) are

58. Unpublished data of L. K. Montgomery. The spectra of 74 and 75 prepared here integrate correctly unlike those of Montgomery (ref. 4).

7475767767716463

also apparent. The 1,2-1,4 adduct assignment had been based originally on the general appearance of the vinyl protons in 74 and 75.⁴ These assignments are now confirmed by degradation of 76 to cyclopentane cis-1,3-dicarboxylic acid and 77 to cyclopentane cis-1,2-dicarboxylic acid by Zn-Cr(II) dehalogenation followed by ozonolysis.

For both 76 and 77 the presence of a geminal CF₂ group is confirmed by an AB quartet (76: J_{AB} = 188 Hz and 77: J_{AB} = 212 Hz) in their rapid sweep ¹⁹F nmr spectra. At a lower sweep rate for 77 fine structure resulting from J_{HF} appears in which one fluorine has been additionally split by 12 and 6 Hz and the other fluorine by 8 and possibly 1 Hz. Analysis of this first order situation affords typical J_{HF} values that can be later used to assign 1212-cyclopentadiene adduct structures.

Work on J_{HF}⁵⁹ indicates that the vicinal coupling between hydrogen and fluorine, J_{HF,12}, follows a dihedral angle, ϕ , relationship much as that between two protons,^{59a, b}

$$J_{HF,12} = \begin{cases} A\cos^2\phi & 0^\circ \leq \phi \leq 90^\circ \\ B\cos^2\phi & 90^\circ \leq \phi \leq 180^\circ \end{cases}$$

While the actual magnitudes of A and B depend considerably on the bond lengths and angles separating hydrogen and fluorine,^{59a} values

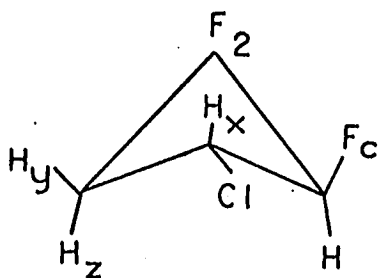
59. a/ A. M. Ihrig and S. L. Smith, J. Am. Chem. Soc., 92, 759(1970).
 b/ K. L. Williamson, Y.-F. L. Hsu, F. H. Hall, S. Swager, and M. S. Coulter, J. Am. Chem. Soc., 90, 6717(1968). c/ K. L. Williamson and J. C. Fenstermaker, J. Am. Chem. Soc., 90, 342 (1968). d/ J. D. Park, R. O. Michael, and R. A. Newmark, J. Org. Chem., 34, 2525(1969).

as great as $A = 31$ Hz and $B = 44$ Hz have been used.^{59b} Regardless of the values chosen for A and B it has been generally found that $J_{\text{HF},12}$ is greater when hydrogen and fluorine are cis, eclipsed ($\phi = 0^\circ$) than when hydrogen and fluorine are trans, skew ($\phi = 120^\circ$).^{59a, b} Since it is assumed that the cyclobutane ring in 77 is planar,⁶⁰ such 0° and 120° angles will be used in the analysis of $J_{\text{HF},12}$ for 77.

An estimate is still needed of the magnitude of vicinal 1,2 coupling through three bonds, $J_{\text{HF},12}$, relative to that of across-the-ring 1,3 coupling through four bonds, $J_{\text{HF},13}$. A model compound, 78, is shown below with 77 for purposes of comparison. Unlike 77 with its planar cyclobutane ring, 78 regrettably has a "W" or "zigzag" 1,3 orientation of fluorine with respect to hydrogen. Such a "zigzag" orientation should serve only to maximize 1,3 interactions.^{59c, 64} From the coupling constants listed below for 78 one concludes that 1,3 across-the-ring couplings are weaker than 1,2 vicinal couplings and that trans 1,3 couplings across a cyclobutane ring are still weaker than the corresponding cis couplings. Assuming these relative magnitudes also hold for the couplings in 77, the coupling constants may be

60. While cyclobutane rings not subject to any constraints are most often puckered, it is generally found that either a C=O group (cyclobutanone) or a C=C group (cyclobutene) is sufficient to planarize the ring.^a Presumably the fused cyclopentane ring in 77 will have a similar planarizing influence. The compound most similar to 77 that has been studied is 7-chloro-6-hydroxybicyclo(3.2.0)hepten-2-yl p-bromobenzoate.^b An X-ray analysis suggests puckered cyclobutane and cyclopentane rings; but, this is hardly surprising in view of the extreme bulk of the p-bromobenzoate group and the fact that analysis was carried out on the crystalline form: a/ J. B. Lambert and J. D. Roberts, J. Am. Chem. Soc., 87, 3884, 3891(1965). b/ P. R. Brook, A. J. Duke, and J. C. R. Duke, Chem. Commun., 574(1970).

assigned as shown below.

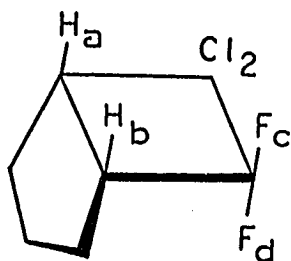


78

$$J_{cx} = 14.7 \text{ Hz}$$

$$J_{cy} = 11.6 \text{ Hz}$$

$$J_{cz} = -3.3 \text{ Hz}$$



77

Fc: 1:1:1:1 quartet

$$J_{bc} = 12 \text{ Hz}$$

$$J_{ac} = 6 \text{ Hz}$$

Fd: 1:1 doublet

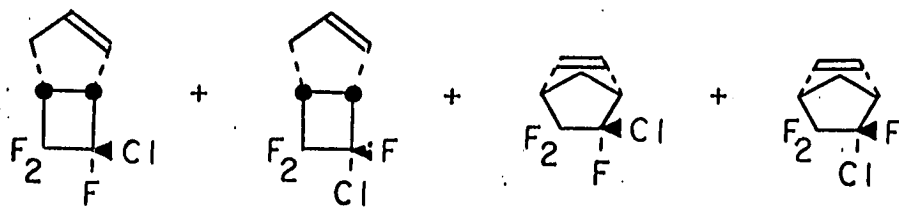
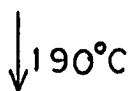
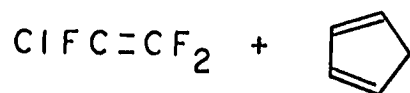
$$J_{bd} = 8 \text{ Hz}$$

6. Cycloaddition of chlorotrifluoroethylene to cyclopentadiene: Thermal cycloaddition of chlorotrifluoroethylene (hereafter designated CTFE) to cyclopentadiene at 190°C affords the adducts 79 to 82. A 20% MNPN vpc column preparatively separated the adducts in the order 79 + 80, 82, 81. With hydrogenation their retention times reordered to 83, 84, 85 + 86 using a 20% Carbowax 20M column. Just as with the 1212-cyclopentadiene adducts judicious staggering of vpc and hydrogenation steps allows preparative separation of all adducts in their hydrogenated form. Mass spectra and proton nmr spectra indicate that hydrogenated cross adducts have truly been isolated. In all cases peaks at mass 149 (-Cl) and mass 68 (C₅H₈⁺) are apparent

Adduct	Mass Spectrum		¹ H Nmr Integration
	Exact Mass ^a	(P+2)/P Ratio ^b	Bridgehead/Bridge Protons
<u>83</u>	184.0271	0.29	2.0/6.0
<u>84</u>	184.0271	0.33	2.0/5.6
<u>85</u>	184.0258	0.35	2.0/6.5
<u>86</u>	184.0258	0.33	2.0/5.8

a. calc. 184.0267 b. 0.33

Dehalogenation with Zn-Cr(II) is run in order to distinguish 1,2 from 1,4 adducts and in order to tentatively assign exo and endo structures. Presumably an adduct with an exo chlorine will react more rapidly than the corresponding endo adduct. Once the 1,2 adducts were identified, the double bond in 79 and 80 was positioned in accord with the greater ability of chlorine than of fluorine to stabilize radical centers in biradicals.

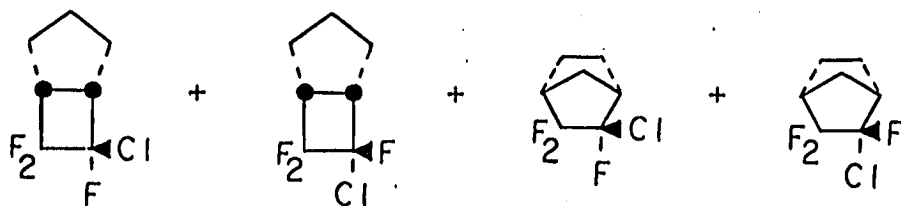
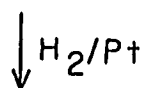


79
14.8

80
16.2

81
42.3

82
26.7

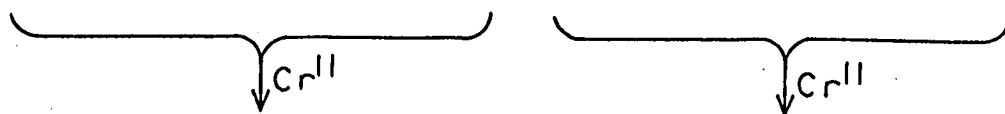


83

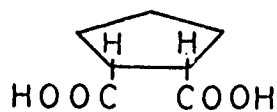
84

85

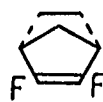
86



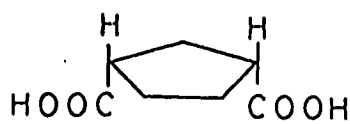
70



63



66

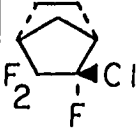
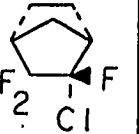
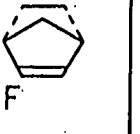
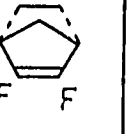


64




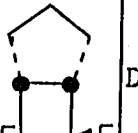
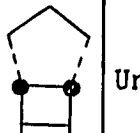
69

Competitive 1,4 Adduct Dehalogenation with Cr(II)^d

			Decalin			Unknown
	<u>85</u>	<u>86</u>		<u>69</u>	<u>66</u>	
Starting Mixture: ^{a, b}	45.1	28.5	26.4			
Product Mixture: ^{a, c}	3.2	22.0	25.4	1.6	44.9	2.9

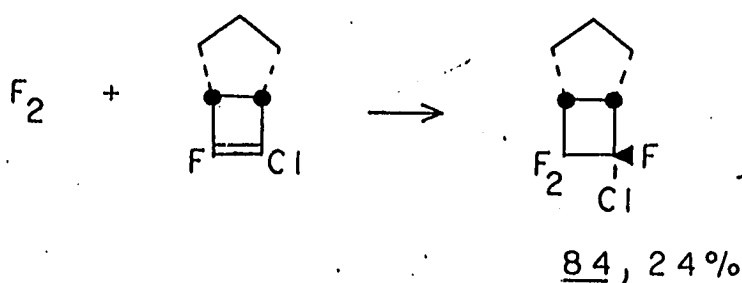
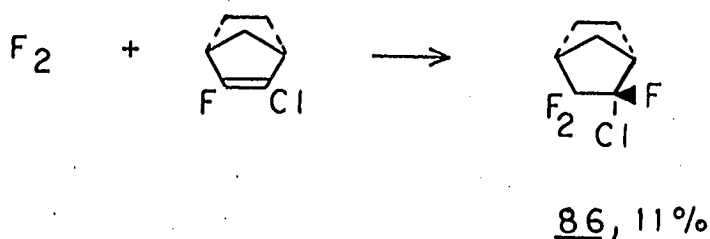
- Uncorrected vpc trace areas.
- Estimated before hydrogenation of 81 and 82 using an MNPN vpc column.
- Percents of 85 and 86 approximate on account of poor vpc separation on Carbowax 20M column used for product analysis.
- 30 mg of adduct-decalin mixture, 0.1 g Zn, 0.1 g $\text{Cr}_2(\text{SO}_4)_3 \cdot n\text{H}_2\text{O}$, 1 ml water, and 1 ml dimethylformamide stirred under nitrogen for 20 hr in a 100°C oil bath.

Competitive 1,2 Adduct Dehalogenation with Cr(II)^b

			Dodecane		Unknown
	<u>83</u>	<u>84</u>		<u>70</u>	
Starting Mixture: ^a	38.7	42.5	17.8		
Product Mixture: ^a	16.3	32.0	17.7	31.4	2.6

- Uncorrected vpc trace area on Carbowax 20M.
- 30 mg of adduct-n-dodecane mixture, 0.1 g of Zn, 0.1 g $\text{Cr}_2(\text{SO}_4)_3 \cdot n\text{H}_2\text{O}$, 1 ml water, 1 ml dimethylformamide stirred under nitrogen for 20 hr in a 100°C oil bath.

Exo, endo assignments are strengthened by using the direct fluorination procedure developed by Merritt.⁶¹ He has found that at -78°C in CFCl_3 fluorine adds to an alkene by competing cis four center and trans ionic mechanisms. Direct fluorination of 67 and 71 produces a multitude of products. In each instance the major product with the vpc retention time of a possible adduct is separated by vpc and found to be identical by ^1H and ^{19}F nmr to that hydrogenated adduct already assigned an exo fluoro structure by Zn-Cr(II) dehalogenation. The percent yields listed represent area percents of the total vpc trace occupied by the adduct isolated from the crude fluorination mixture.



61. a/ R. F. Merritt and T. E. Stevens, J. Am. Chem. Soc., 88, 1822 (1966). b/ R. F. Merritt, J. Org. Chem., 31, 3871(1966). c/ R. F. Merritt and F. A. Johnson, J. Org. Chem., 31, 1859(1966). d/ R. F. Merritt, J. Am. Chem. Soc., 89, 609(1967).

This treatment, of course, assumes that exo cis difluorination will be preferred to endo cis difluorination.

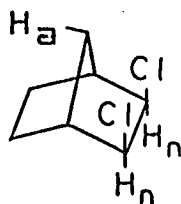
Fluorine-19 nmr spectra are consistent with structure assignments. Assuming no accidental overlaps between an AB quartet for the CF_2 group and a single multiplet for the $CFCl$ group a five line spectrum is expected on fast sweep. This is in fact observed for 83 and 86 whereas accidental overlaps occur for 84 and 85. Significantly the $CFCl$ ^{19}F multiplet in 84 has a width of 20 Hz while the corresponding multiplet in 83 has a width of 10 Hz (see spectra), the greater width of 84 being expected on the basis of coupling constants previously extracted from analysis of 77.

7. Assignment of halogen configuration by ^{19}F nmr: Assignment of cis and trans halogen configuration is quite easy for the hydrogenated 1,2,1,2-cyclopentadiene adducts 57-62. The two trans adducts 58 and 61 have nonequivalent fluorines and hence two distinct multiplets in their ^{19}F nmr spectra in contrast to the four cis adducts 57, 59, 60, and 62 which have equivalent fluorines and hence only single multiplets in their ^{19}F nmr spectra.

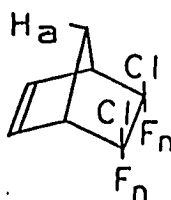
Fine structure may be used to distinguish exo and endo cis adducts from one another. For 1,4 adducts 56 and 62 an entirely analogous case exists in 1H nmr. The protons H_n in 87 appear as a

62. O. Wersel, Bartlett Group Report #VIII, March, 1967, unpublished.

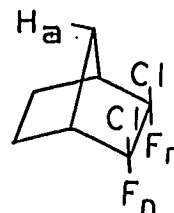
1:1 doublet as do the fluorines F_n in 56⁶³ or 62. The doublets of 56, 62, and 87 are simply further examples of the long range four bond couplings that occur in bicyclic compounds when two hydrogens⁶⁴ or a hydrogen and a fluorine⁶⁰ are held in a rigid, planar "W" or "zigzag" relationship.

87

$$J_{H_a H_n} = 2 \text{ Hz}$$

56

$$J_{H_a F_n} = 4 \text{ Hz}$$

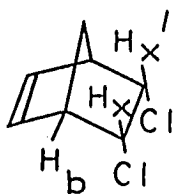
62

$$J_{H_a F_n} = 4 \text{ Hz}$$

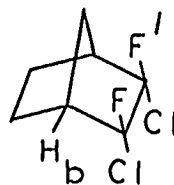
56. Evidence for the structure of 56: The mass spectrum has a parent peak of exact mass 197.9798 (calc. 197.9995) and (P+2)/P ratio of 0.67 (calc. 0.65). The mass spectrum has a base peak at mass 66 corresponding to $C_5H_6^+$ (cyclopentadiene⁺) formed in a retro Diels-Alder reaction. The ¹H nmr shows a 2H 1:2:1 vinyl triplet at 6.2 δ, a 2H bridgehead multiplet at 3.4 δ, and a 2H methylene bridge multiplet at 2.0 δ. This material was preparatively separated by vpc using Carbowax 20M with the crude 1212-cyclopentadiene adduct mixture.

64. a/ P. Laszlo and P. von Rague Schleyer, *J. Am. Chem. Soc.*, 86, 1171(1964). b/ F. A. L. Anet, *Can. J. Chem.*, 39, 789(1961). c/ K. B. Wiberg, B. R. Lowry, and B. J. Nist, *J. Am. Chem. Soc.*, 84, 1594(1962). d/ A. Rassat, C. W. Jefford, J. M. Lehn, and B. Waegell, *Tetrahedron Lett.*, 233(1964). e/ J. Meinwald and A. Lewis, *J. Am. Chem. Soc.*, 83, 2769(1961). f/ S. Sternhell, *Rev. Pure Appl. Chem.*, 14, 15(1964).

The protons H_x and H_x' appear as a 1:2:1 triplet in 88^{64a} as do the fluorines F and F' in 61. In both cases the triplet arises from the phenomenon of "virtual coupling"^{65a} which has been treated independently by a number of authors.⁶⁵ Essentially, one group of nuclei is internally coupled sufficiently strongly with respect to any internal chemical shift differences or external couplings that this group will accept and transmit spin-spin effects as a single unit. In 61 F and F' are coupled to the two bridgehead protons so as to be split into a triplet. In such cases the coupling constants cannot be derived by first order analysis; rather, the separation between the two outer lines of the 60 triplet is equal to the algebraic sum $J_{H_bF} + J_{H_bF'}$.

88

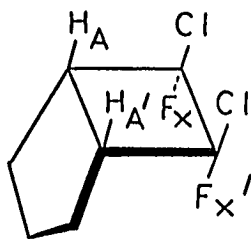
$$J_{H_bH_x} + J_{H_bH_x'} = 3.2 \text{ Hz}$$

60

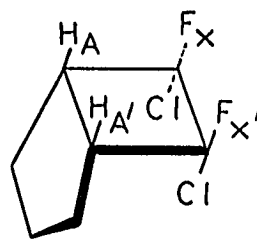
$$J_{H_bF} + J_{H_bF'} = 11 \text{ Hz}$$

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65. a/ J. I. Musher and E. J. Corey, Tetrahedron, 18, 791(1962).
 b/ R. J. Abraham and J. J. Bernstein, Can. J. Chem., 39, 216(1961).
 c/ K. B. Wiberg and B. J. Nist, The Interpretation of NMR Spectra, W. A. Benjamin, Inc., New York, N. Y., 1962.

Exo cis 1,2 adduct 59 may also be distinguished from its corresponding endo cis adduct 57 by ^{19}F nmr. The bridgehead protons H_A and $\text{H}_{\text{A}'}$ of 57 and 59 couple to the two cis fluorines F_X and $\text{F}_{\text{X}'}$, forming an $\text{AA}'\text{XX}'$ system. While a complete analysis of these ^{19}F nmr spectra requires resolution of all ten lines calculated by theory, partial analysis may nonetheless be carried out on more poorly resolved systems. The two strongest lines, generally located towards the outside, in an $\text{AA}'\text{XX}'$ spectrum are separated by $J_{\text{AX}} + J_{\text{AX}'}$.⁶⁶ Using the coupling constants found for bicyclo(3.2.0)heptanes in the first order analysis of 77, $J_{\text{AX}} + J_{\text{AX}'}$ may be estimated as 8 Hz for 57 and 18 Hz for 59. These values compare well with the experimentally observed values of 6 and 26 Hz respectively.

57

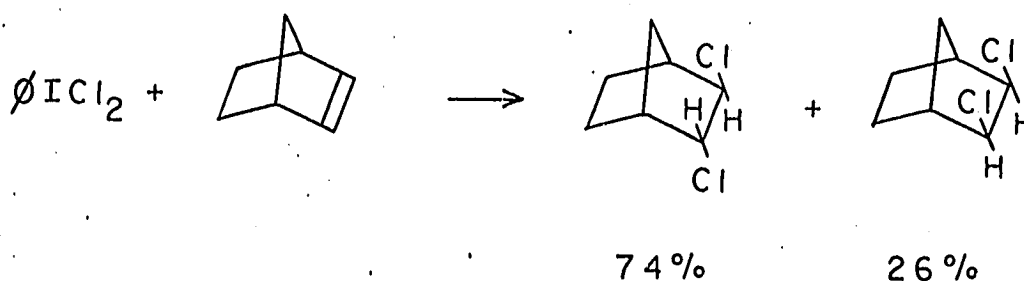
$$J_{\text{AX}} + J_{\text{AX}'} = 6 \text{ Hz (calc. 8 Hz)}$$

59

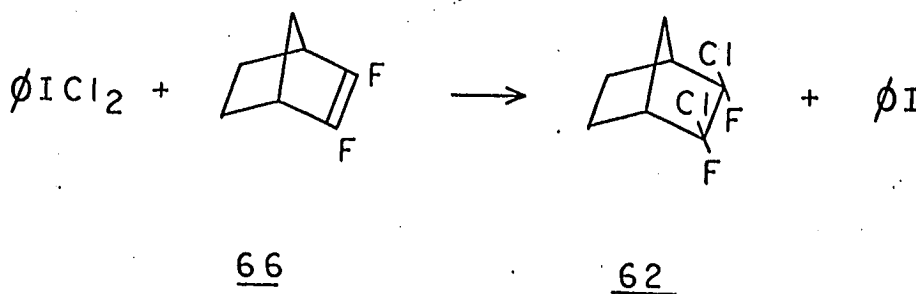
$$J_{\text{AX}} + J_{\text{AX}'} = 26 \text{ Hz (calc. 18 Hz)}$$

66. a/ K. B. Wiberg, Physical Organic Chemistry, John Wiley and Sons, Inc., New York, 1966, pp. 492-94. b/ J. A. Pople, W. G. Schneider, and H. J. Bernstein, High Resolution Nuclear Magnetic Resonance, McGraw-Hill Book Company, Inc., New York, 1959, p. 140.

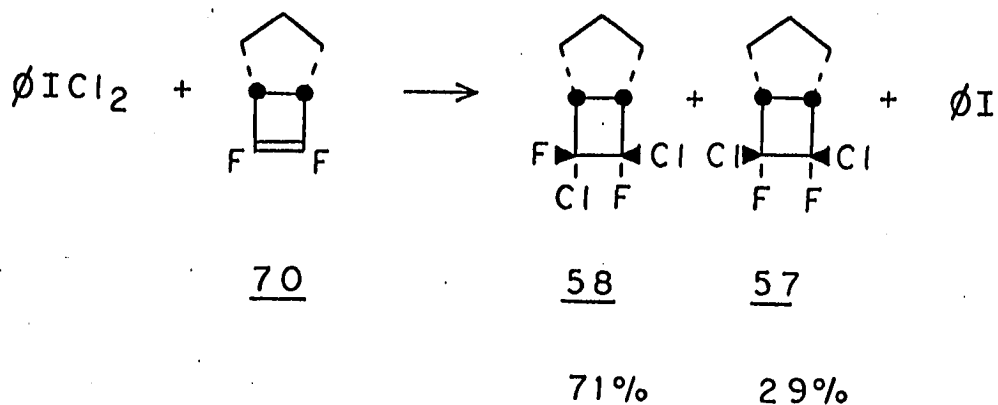
8. Independent synthesis of adducts: As a final check on degradative and spectral structure assignments the four cis adducts 57, 59, 60, and 62 were synthesized independently. Tanner^{67a} in refining a procedure of Poutsma^{67b} has demonstrated that iodobenzene dichloride can dichlorinate norbornene by a clean free radical chain mechanism. Consistent with intuitive expectations exo cis dichlorination is apparently favored over endo cis dichlorination.



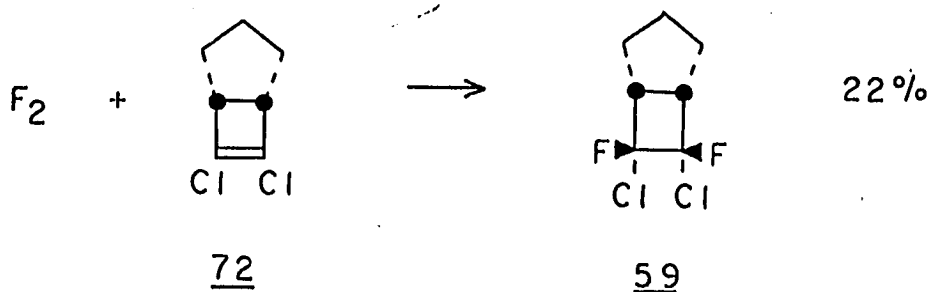
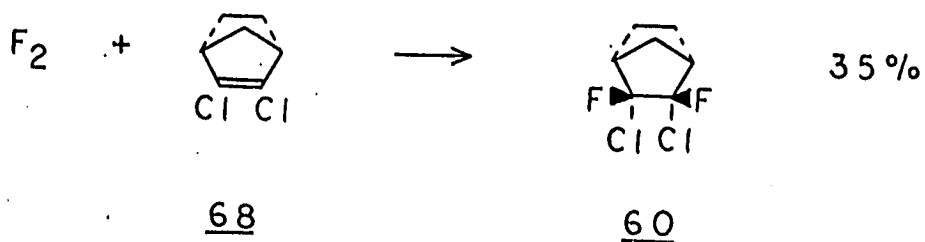
Similarly iodobenzene dichloride chlorination of 66 and 70 leads to exo cis dichloro adducts 62 and 57 in preference to endo cis dichloro adducts 59 and 60. The ¹H and ¹⁹F nmr spectra of 62, 57, and 58 obtained in this manner agree with those of genuine cycloadducts.



67. a/ D. D. Tanner and G. C. Gidley, *J. Org. Chem.*, **33**, 38(1968).
 b/ M. L. Poutsma, *J. Am. Chem. Soc.*, **87**, 4293(1965).



Again with the assumption that exo cis difluorination will be preferred over competing endo cis difluorination, direct fluorination of 68 and 72 was carried out at -78°C in CFCl_3 . In each case



the major product was separated from a multitude of side products using a Carbowax 20M vpc column and found to have a ^1H and ^{19}F nmr spectrum identical to that of genuine cycloadduct 60 or 59. Neither of the adducts previously assigned endo cis difluoro structures 58 and 62 could be demonstrated to be present in significant quantities.

9. Separation of cis- from trans-1212: Even though structures have now been assigned to the 1212-cyclopentadiene adducts, configurational studies cannot be completed until cis- and trans-1212 are available. The original paper reported separation by distillation.^{68a} Tiers and Lauterbur, however, could not reproduce this separation, obtaining only slight enrichment at best as indicated by analysis of the ABX ^{13}C satellites in the ^{19}F nmr spectrum of 1212.^{68b} Employing preparative vpc Craig and Evans separated crude 1122 into two fractions.^{68c} The first fraction proved to be 1122 whereas the second had the IR spectrum previously reported for trans-1212^{68d} but was in fact a cis- plus trans-1212 mixture. Starting again with a sample of 1212 from which contaminating 1122 had been removed chemically, Craig and Evans now obtained 99.6% trans-1212 and 95.1% cis-1212 by a tedious fractional melting procedure in conjunction with distillation.^{68c}

68. a/ E. G. Locke, W. R. Brode, and A. L. Henne, J. Am. Chem. Soc., 56, 1726(1934). b/ G. V. D. Tiers and P. C. Lauterbur, J. Chem. Phys., 36, 1110(1962). c/ N. C. Craig and D. A. Evans, J. Am. Chem. Soc., 87, 4223(1965). d/ D. E. Mann and E. K. Plyler, J. Chem. Phys., 26, 773(1957).

Previous attempts to separate cis- from trans-1212 by vpc have failed.^{68b, c} After trying some 27 combinations, we found that rather volatile, highly polar liquid phases such as dimethylsulfoxide, dimethylsulfone, and dimethylformamide on 80-100 mesh Alcoa F-20 Chromatographic Alumina are particularly successful. A high proportion of liquid phase relative to solid support leads to reduced retention times with loss of resolution whereas a low proportion of liquid phase leads to extended retention times with blurring of resolution. Thus roughly 5% by weight liquid phase is generally optimal. Liquid phases such as dimethylsulfoxide are sufficiently volatile that the columns are not baked out but rather put into immediate use at 0-25°C. Even so the retention times tend to become longer with continued use presumably as a result of gradual stripping of the liquid phase.

Vpc analysis of 1212 obtained from Peninsular Chemresearch Inc. reveals two major components with roughly 5-10% of a third component that has the retention time of 1122. This common impurity in 1212 is removed by refluxing with sodium ethoxide in ethanol.^{68c} The purified 1212 is then collected preparatively using a 7M X $\frac{1}{4}$ " , 5% DMSO on 80/100 mesh alumina column at room temperature. Comparison to published IR spectra^{68c} distinguishes the two isomers, trans-1212 eluting before cis-1212.

10. Thermal addition of cis- and trans-1212 to cyclopentadiene:

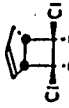
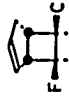
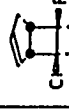

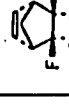

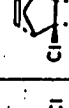
In the presence of hydroquinone 99% pure trans-1212 and 95-96% pure cis-1212 are cycloadded to cyclopentadiene under nitrogen at 180-195°C for 8 hr. The results are shown in Table III. On cycloaddition of 99% trans-1212, the resulting 1,2 adducts have 80% trans halogen configuration and the resulting 1,4 adducts 99% trans halogen configuration. On cycloaddition of 95-96% cis-1212, the resulting 1,2 adducts have 70% cis halogen configuration and the resulting 1,4 adducts 93% cis halogen configuration. The 1-7% loss of configuration in the 1,4 adducts is essentially the same as the 1-5% cis and trans impurities present in the starting 1212 implying that the 1,4 adducts are formed by a concerted one-step mechanism. The 20-30% loss of configuration in the 1,2 adducts cannot be explained in terms of cis and trans impurities in the starting 1212 but rather in terms of a freely rotating biradical intermediate. Thus, 1,2 versus 1,4 competition arises as a result of competition between biradical and concerted modes of cycloaddition.

Control experiments indicate that cis- and trans-1212 do not interconvert under the reaction conditions since the purity of trans-1212 both before and after cycloaddition is 99% and the purity of cis-1212 is 96% before cycloaddition and 95% on recovery after cycloaddition.

It was necessary to demonstrate that the adducts neither significantly interconvert nor decompose under the reaction conditions.

TABLE III

CYCLOADDITION OF CYCLOPENTADIENE TO ClFC=CFCI

MODE OF ADDITION	CONFIGURATION OF 1212 ^a		UNCORRECTED VPC TRACE AREA ^{b,c}							
	START	FINISH								DIMERS
THERMAL, 180-95°C	99% TRANS	99% TRANS	0.2	1.2	1.0	0.3	0.0	96.7	0.6	241
THERMAL, 180-95°C	96% CIS	95% CIS	24	0.9	1.0	1.7	27.3	64	60.3	242
PHOTOSENSITIZED	99% TRANS	97% TRANS	56	15.7	252	15.7	11.7	25.4	0.7	570
PHOTOSENSITIZED	96% CIS	93% CIS	5.0	11.5	40.0	19.2	6.2	16.3	1.8	440

^a 125M X 1/8", 5% DMSO, 80/100 alumina, 0°C, F&M Scientific Model 700 vpc

^b 10M X 1/8", 20% Carbowax 20M, 60/80W, 160°C, F&M Scientific Model 700 vpc

^c Adduct areas sum to 100.

This is a serious consideration inasmuch as thermal conversions of bicyclo(3.2.0)hept-2-enes to norbornenes have been reported.⁶⁹ Such rearrangements, however, do not normally occur until temperatures (roughly 300°C) considerably higher than those employed in our cycloadditions. Heating adduct mixtures rich in either 1,2 or 1,4 adducts at 210-225°C causes neither significant redistribution nor diminution in the adducts 50-56.

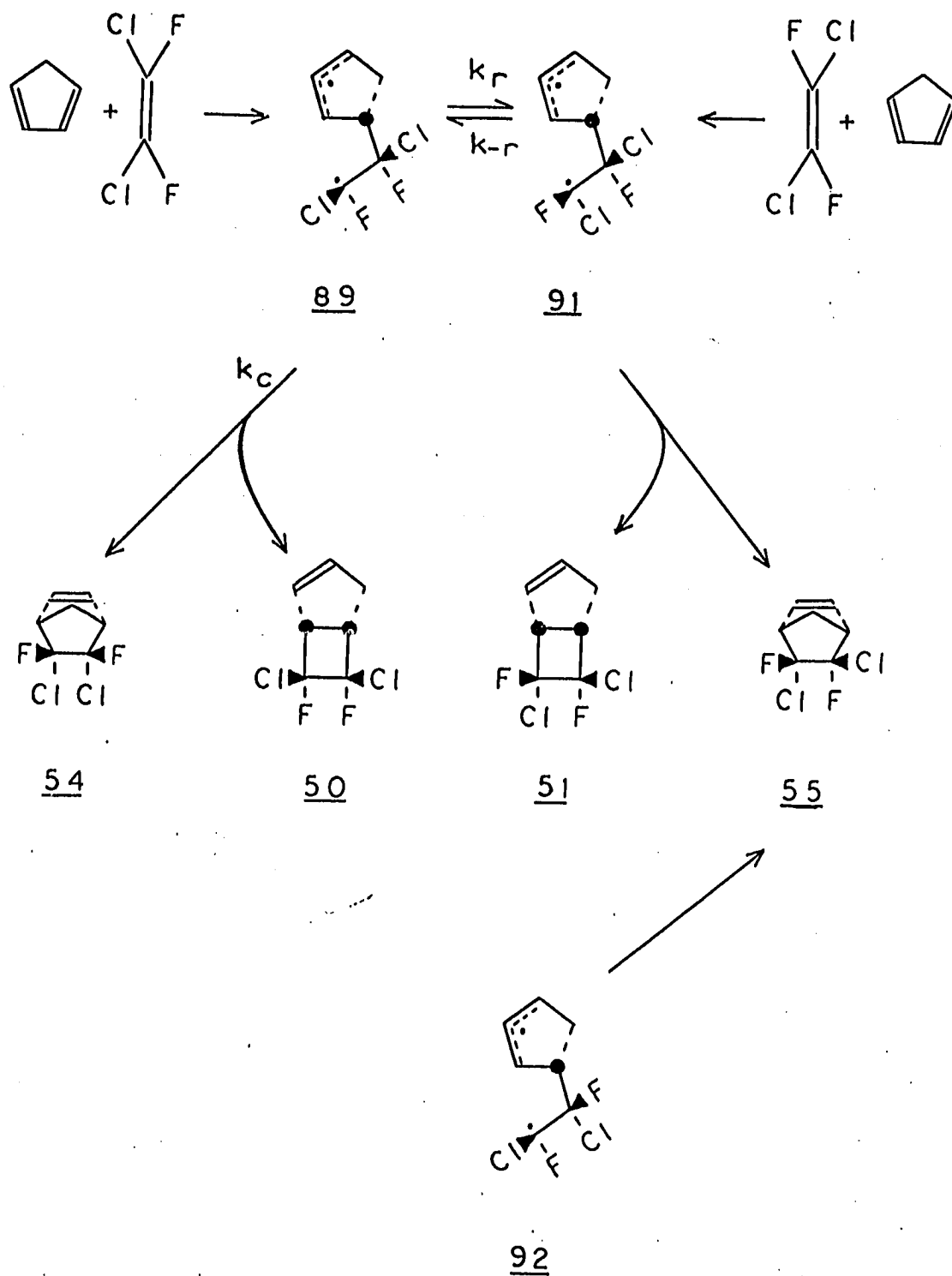
11. Photosensitized cycloaddition of 1212 to cyclopentadiene: Irradiation of 1212 and cyclopentadiene through Pyrex at room temperature in the presence of β -acetonaphthone gives the results shown in the lower lines of Table III. Consistent with previous structure assignments the percentage of 1,2 adduct relative to 1,4 adduct increases sharply on photosensitization compared to the corresponding thermal cycloaddition as has been observed in numerous other systems.^{47, 48, 50}

Now the 1,4 adducts are formed with loss of configuration as well as the 1,2 adducts demonstrating that a 1,6 biradical from 1212 and cyclopentadiene may be expected to show loss of configuration at least when in a triplet state. By extension a singlet biradical that closes 1,6 would also be expected to show loss of configuration. That is, perhaps those biradicals responsible for the 6% of 1,2

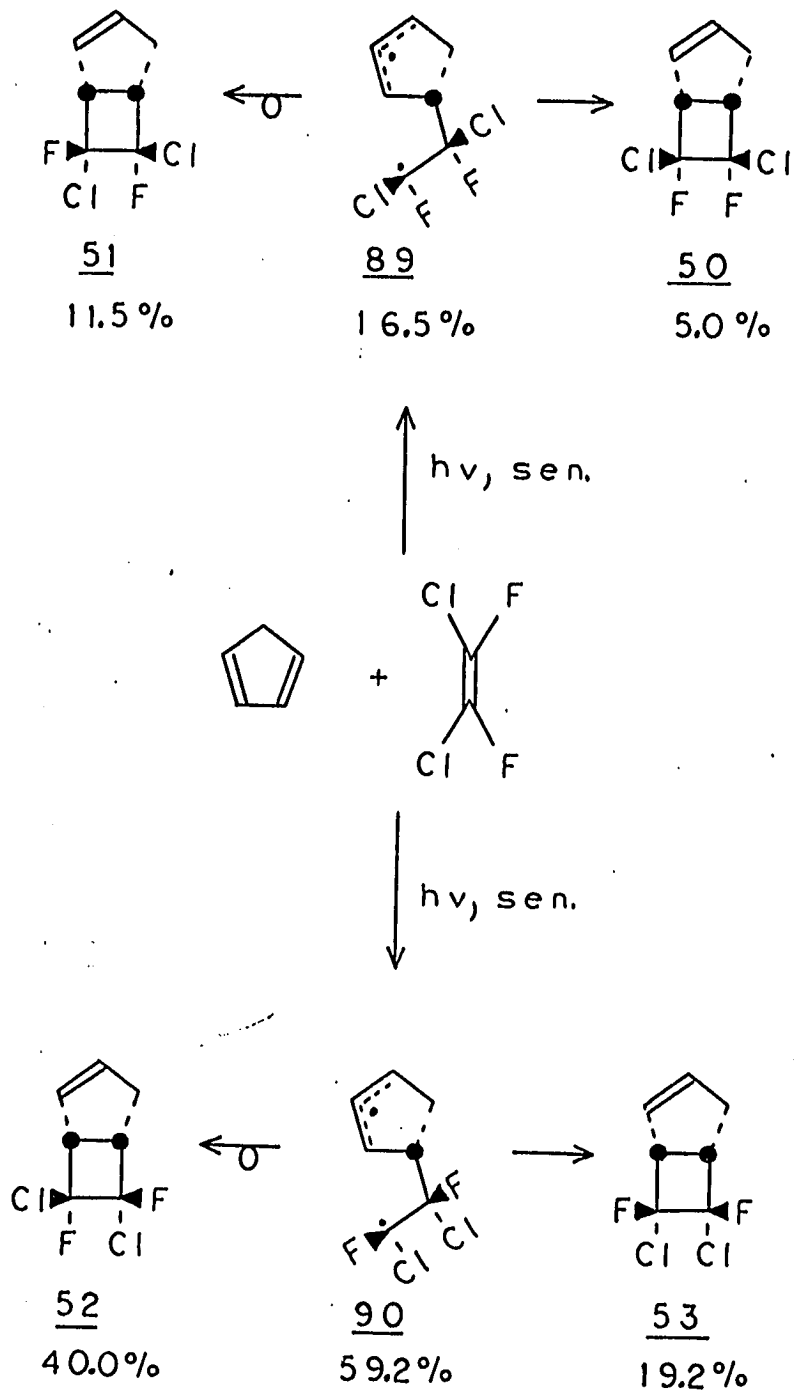
69. a/ J. A. Berson and G. L. Nelson, J. Am. Chem. Soc., 92, 1096 (1970). b/ J. A. Berson and G. L. Nelson, J. Am. Chem. Soc., 89, 5503(1967).

adducts formed also cross over to some extent to 1,4 adducts with lost configurations. Regrettably it is not possible to give a quantitative distribution of the 0-3% 1,4 adducts formed by a biradical process in that they are masked by the much larger portion of 1,4 adducts simultaneously formed by a Diels-Alder reaction. This uncertainty mars later distinctions that are to be drawn between singlet and triplet biradicals.

This is the first example allowing direct comparison of the configurational behavior of singlet and triplet biradicals on cycloaddition. On thermal cycloaddition the 1,2 adducts between 1212 and cyclopentadiene show 20-30% loss of cis, trans configuration. On photosensitized cycloaddition both 1,2 and 1,4 adducts between 1212 and cyclopentadiene show 30-70% loss of cis, trans configuration. Apparently the triplet biradical in photosensitized cycloaddition is longer-lived and/or starts in a more extended conformation than the corresponding singlet biradical from thermal cycloaddition thus allowing greater rotation and loss of configuration.⁴⁵ It is felt that there are too many uncertainties to attempt a numerical calculation of relative rate of closure to rotation, k_c/k_r , for the singlet and triplet biradical precursors. In order to apply the method of Montgomery, Schueller, and Bartlett¹¹ one would have to have confidence in the structure assignments for 51 and 52 (see section #12), would have to know the extent to which 89 and 91 give 1,4 adducts on thermal cycloaddition, and would have to know the extent to which 55 is formed from diastereomers 91 and 92.



12. Tentative assignment of structures 51 and 52: Structures 51 and 52 can now be tentatively assigned on the basis of adduct distribution. The product distributions for the photochemical adduct mixtures rather than for the thermal adduct mixtures will be employed because (1) fuller rotational equilibrium is expected in the photochemical additions than in the thermal additions and (2) differences in the relative quantities of 1,2 adducts are much greater in the photochemical additions and do not border on experimental error as in the thermal additions. In the photosensitized cycloaddition of 1212 to cyclopentadiene consider pairs of 1,2 adducts consisting of one cis and one trans adduct derived from the same biradical intermediate. For example, in the reaction of cis-1212 with cyclopentadiene there are two such pairs: 50 + 51 and 52 + 53. Apparently biradical 90 is formed to a greater extent than biradical 89 since there is 19.2% of 53 but only 5.0% of 50. If one next assumes that the loss of configuration by rotation occurs to a comparable extent in 89 and 90, then more trans 1,2 adduct shall be formed from more populated biradical 90 than the less populated biradical 89 in which case the 40.0% trans 1,2 adduct corresponds to 52 and the 11.5% trans 1,2 adduct to 51. Admittedly the assumption of equal degrees of rotation in diastereomeric biradicals 89 and 90 may not be entirely justified and the opposite assignments would be obtained considering the thermal 1,2 adduct distributions. The assignments for 51 and 52 must thus be viewed with extreme caution.



II. Origin of Biradical Reactivity in Fluoroalkenes:

A. Statement of problem

Substitution of fluorine in an alkene that is to be cycloadded to a diene frequently causes (2+2) biradical cycloaddition to compete with normally dominant (2+4) Diels-Alder cycloaddition. For example, $\text{FClC}=\text{CClF}$ and $\text{FClC}=\text{CF}_2$ cycloadd 1,2 as well as 1,4 to cyclopentadiene whereas $\text{HClC}=\text{CClH}$ and $\text{HClC}=\text{CH}_2$ cycloadd just 1,4.^{49h, 70} Similarly $\text{F}_2\text{C}=\text{CF}_2$ cycloadds just 1,2 to butadiene⁷¹ whereas $\text{H}_2\text{C}=\text{CH}_2$ cycloadds at least 99.98% 1,4.⁴⁴

Roberts and Sharts have suggested that interelectronic repulsion between two geminal fluorines opens the F-C-F angle in a fluoroalkene while simultaneously decreasing the angle between the other two carbon valences. This decreased angle between the two carbon valences is such as to favor cyclobutane rings over cyclohexene rings and hence (2+2) biradical over (2+4) cycloaddition.^{2a} Huisgen has cited the normal F-C-F bond angle of 109.5° in octafluoropropane and the small 114° angle in tetrafluoroethylene as evidence that such distortions do not in fact occur.^{19a} Such distortions further imply a special stability for fluorinated cyclobutanes, but Bennett⁷² estimates that perfluorocyclobutane is even more strained than cyclobutane itself. Even though 1,2,1,2 lacks the geminal CF_2 groups that are to be

70. E. C. Kooyman and G. C. Vegter, Tetrahedron, 4, 382(1958).

71. D. D. Coffmann, P. L. Barrick, R. D. Cramer, and M. S. Raasch, J. Am. Chem. Soc., 71, 490(1949).

72. W. A. Bennett, J. Org. Chem., 34, 1772(1969).

distorted, it still shows characteristic biradical activation by fluorine. Dichloromethylenecyclopropane behaves quite like 1122 (see below) inspite of angular relationships exactly opposite those in the presumably distorted CF_2 groups of fluoroalkanes. This model may thus be discounted.

Montgomery, Schueller, and Bartlett have proposed that electron delocalization energy and fluoroalkene destabilization may contribute to biradical reactivity by lowering the barrier to biradical formation.¹¹ While these factors could conceivably have a similar activating effect on the competing Diels-Alder reaction, rough calculations in later papers suggest that indeed 1,2 biradical cycloaddition is much more sensitive to the substitution of olefinic destabilizing groups (fluorine) and electron delocalizing groups (chlorine):

Relative Rates of 1,2 and 1,4 Addition
to Butadiene at 175°C

Dienophile	$k_{1,2}$	$k_{1,4}$	
$\text{H}_2\text{C}=\text{CH}_2$	10^{-7}	10^{-3}	
$\text{H}_2\text{C}=\text{C}(\text{CN})\text{OAc}$	10^{-3}	10^{-2}	(44)
$\text{F}_2\text{C}=\text{CCl}_2$	1	10^{-2}	

Relative Rates of 1,2 and 1,4 Addition
to Butadiene at 212°C

Dienophile	$k_{1,2}$	$k_{1,4}$
$H_2C=CH_2$	10^{-7}	10^{-3}
$H_2C=CF_2$	10^{-5}	10^{-4}
$F_2C=CFH$	10^{-3}	10^{-4}
$F_2C=CF_2$	1	10^{-2}

In each series the rate of 1,2 addition varies roughly five powers of ten more than the rate of 1,4 addition for the same reactant pairs. Since none of the dienophiles studied above have drastically different steric requirements, rate variation probably derives chiefly from changes in E_a or ΔH^\ddagger rather than from changes in $\log A$ or ΔS^\ddagger . In fact Sauer and coworkers have verified this for Diels-Alder reactions between cyclopentadiene and over 30 dienophiles (10^8 rate variation), 9, 10-dimethylanthracene and over 30 dienophiles (10^6 rate variation), maleic anhydride and over 30 dienes (10^6 rate variation), and hexchlorocyclopentadiene and numerous dienophiles.^{24, 25} Substitution of fluorine and electron delocalizing groups on a double bond apparently lowers ΔH^\ddagger for biradical cycloaddition relative to that for competing Diels-Alder cycloaddition. Eventually the point is reached where the rate of biradical cycloaddition overtakes and passes that of Diels-Alder cycloaddition.

Fluorine substitution and electron delocalization may be examined individually. The thermal dimerization of dienes such as butadiene^{73a, b} and chloroprene^{73c}, for example, gives rise to typical biradical products including 1,2-divinylcyclobutanes and 1,5-cyclooctadienes. The biradicals required to form these products have two allylic centers with a potential 50 kcal/mole^{2b} of electron delocalization energy. On the other hand biradical dimerization of tetrafluoroethylene⁷⁴ proceeds readily without the aid of any delocalization energy. Thus, both fluorine substitution and electron delocalization appear independent and sufficient in themselves to initiate biradical reactivity, and further discussion will be limited primarily to the influence of fluoroalkene substitution.

Thus far, enhanced biradical reactivity in fluoroalkene has been attributed to fluoroalkene destabilization. Inasmuch, however, as biradical and concerted cycloadditions ultimately achieve the same relief of destabilization energy it is not immediately obvious why this relief accelerates biradical relative to concerted cycloaddition. Furthermore this treatment completely ignores other unique factors in fluoroalkene chemistry such as olefinic rehybridization and strong electron withdrawal. The next section attempts to integrate all three factors -- destabilization, rehybridization, and electron withdrawal --

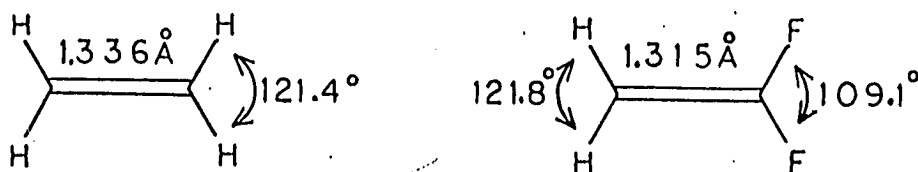
73. a/ H. W. B. Read, *J. Chem. Soc.*, 685(1951). b/ S. W. Benson, *J. Chem. Phys.*, 46, 4920(1967). c/ A. C. Cope and W. R. Schmitz, *J. Am. Chem. Soc.*, 72, 3056(1950).

74. J. R. Lacher, G. W. Tompkin, and J. D. Park, *J. Am. Chem. Soc.*, 74, 1693(1952).

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into a consistent explanation of fluoroalkene biradical reactivity.

Before proceeding to the next section, however, the relationships between and evidence for electron withdrawal, olefinic rehybridization, and olefinic destabilization in fluoroalkenes should be reviewed. Fluorine is strongly electron withdrawing as seen by its Hammett σ_m value of 0.34.⁷⁵ In the face of such strong electron withdrawal p character concentrates in those carbon orbitals extending to fluorine.⁷⁶ Carbon centers that are normally sp^2 , for example, tend increasingly towards sp^3 with increasing fluorine substitution. In particular a hyperfine splitting of 38.5 gauss on the part of ^{13}C in the methyl radical indicates roughly sp^2 planar hybridization in contrast to 271.6 gauss for the trifluoromethyl radical indicating sp^4 pyramidal.⁷⁷ A similar effect is seen in fluoroalkenes. Electron diffraction data for ethylene⁷⁸ and microwave data for vinylidene fluoride⁷⁹ are shown below,



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75. E. S. Gould, Mechanism and Structure in Organic Chemistry, Holt, Rhinehart, and Winston, New York, 1959, p. 221.
76. H. A. Bent, Chem. Rev., 61, 275(1961).
77. R. W. Fessenden and R. H. Schuler, J. Chem. Phys., 43, 2704(1965).
78. L. S. Bartell, E. A. Roth, C. D. Hollowell, K. Kuchitsu, and J. E. Young, Jr., J. Chem. Phys., 42, 2683(1965).
79. W. V. Laurie and D. T. Pence, J. Chem. Phys., 38, 2693(1963).

The H-C-H angles in ethylene and vinylidene fluoride correspond to sp^2 hybridization whereas the F-C-F angle in vinylidene fluoride corresponds to sp^3 hybridization.⁷² According to Bennett conversion of an alkene $C_{sp^2}H$ bond to a weaker alkane $C_{sp^3}H$ bond makes the energy of alkene to alkane conversion greater than might otherwise be expected. Since fluoroalkenes already have the sp^3 hybridization of fluoroalkanes, there is not an analogous hidden energy to be overcome in the conversion of a fluoroalkene to a fluoroalkane. Thus, fluoroalkenes which do not have strong $C_{sp^2}F$ bonds as alkenes have $C_{sp^2}H$ bonds can be said to be destabilized relative to alkenes.

Patrick has collected data illustrating the net effect of such destabilization.⁸⁰

(Heat of Chlorination of Designated Fluoroalkene) -
(Heat of Chlorination of Ethylene)

$F_2C=CF_2$	-15.8 kcal/mole
$F_2C=CFCl$	- 7.3 kcal/mole
$F_2C=CFCF_3$	- 5.7 kcal/mole
$F_2C=C(CF_3)_2$	+ 0.7 kcal/mole

(Heat of Hydrobromination of Designated Fluoroalkene) -
(Heat of Hydrobromination of Ethylene)

$F_2C=CF_2$	-16.2 kcal/mole
$F_2C=CFCl$	- 9.3 kcal/mole
$F_2C=CCl_2$	- 5.2 kcal/mole

80. C. R. Patrick, Tetrahedron, 4, 26(1958).

Clearly tetrafluoroethylene is roughly 16 kcal/mole more exothermic in its heats of chlorination and hydrobromination than is ethylene and this exothermicity (presumably reflecting olefinic destabilization⁸¹) decreases with successive replacement of the fluorines by such groups as chlorine and trifluoromethyl. For later reference it is noted here that trifluoromethyl appears to exert a considerable stabilizing effect since the destabilization caused by geminal CF₂ in perfluoroisobutylene is quite overcome by the stabilizing effect of two trifluoromethyl groups. The net effect of such destabilization on the favorability of four membered rings is seen in the comparison of cyclobutene to perfluorocyclobutene. Cyclobutene isomerizes irreversibly to butadiene at 150°C^{82a} in contrast to perfluorobutadiene which isomerizes to perfluorocyclobutene at 260°C.^{82b} This favoring of the fluorinated cyclobutane ring does not reflect any particular stability associated with fluorination since perfluorocyclobutane has 32 kcal/mole of ring strain (combustion) and cyclobutane only 26 kcal/mole of ring strain (combustion).⁷² Rather the driving force is simply the extra energy gained on going from fluoroalkene to fluoroalkane compared to a normal alkene to alkane conversion.

81. The usual convention of fluoroalkene destabilization has been followed here although the thermodynamic data are equally consistent with viewing fluoroalkenes to be of normal energy and fluoroalkanes to be exceptionally stabilized. This distinction makes no difference in the subsequent treatment of biradical reactivity. Rather only the fact that an exceptional amount of energy is released in a fluoroalkene to fluoroalkane conversion is important.

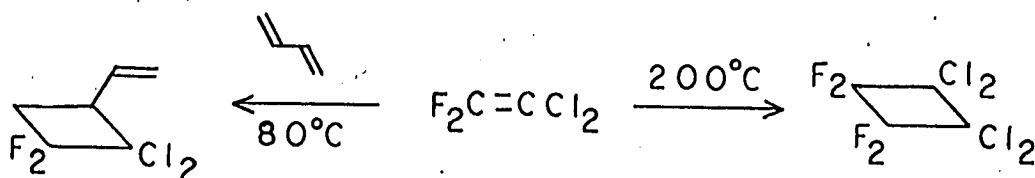
82. a/ W. P. Hauser and W. D. Walters, J. Phys. Chem., 67, 1328(1963).
b/ E. W. Schlag and W. B. Peatman, J. Am. Chem. Soc., 86, 1676(1964).

B. Biradical reactivity arising from fluoroalkene destabilization

1. Model compounds based on 1122

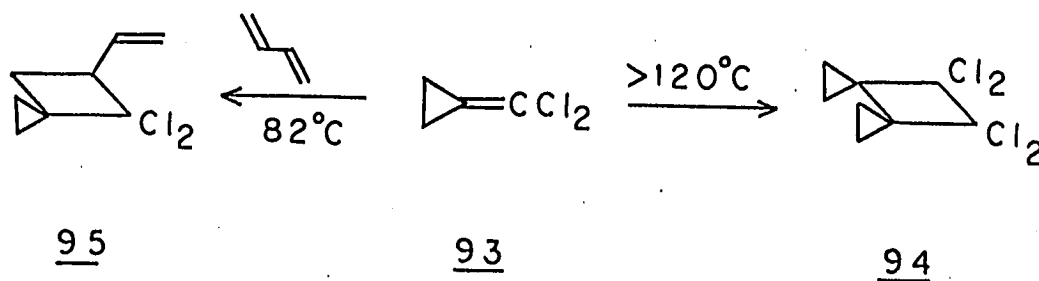
a. Dichloromethylenecyclopropane: 1,1-Dichloro-2,2-difluoroethylene (1122) is a typical fluoroalkene in that it both cycloadds 1,2 to butadiene⁵³ and dimerizes³ with the orientation required by a most stable biradical intermediate. Replacement of the CF_2 group in this model fluoroalkene, 1122, by alternate groups allows isolation of those unique factors -- electron withdrawal, olefinic destabilization, and/or olefinic rehybridization -- felt to be responsible for biradical reactivity.

If the CF_2 group of 1122 is replaced by cyclopropyl, there results dichloromethylenecyclopropane, 93. In another connection Dolbier, Lomas, and Tarrant have already shown that dichloromethylenecyclopropane dimerizes head-to-head at temperatures higher than 120°C .⁸³ Vpc on Carbowax 20M of the reaction mixture obtained by heating dichloromethylenecyclopropane for 60 hr with an excess of butadiene at 80°C indicates



4

83. W. R. Dolbier, Jr., D. Lomas, and P. Tarrant, J. Am. Chem. Soc., 90, 3594(1968).



essentially a single 1,2 adduct 95. Elemental analysis of a vpc pure sample is correct for the cross adduct between butadiene and dichloromethylenecyclopropane. No parent peak was apparent in the mass spectrum but the major fragments were consistent with the assigned cross adduct structure:

Mass	Fragment Structure	(P+2)/P Ratio	% Base Peak
39			96
51	$C_4H_3^+$		100
54	or		27
122	or	0.67	19
141		0.33	14

The IR spectrum is consistent with structure 95 showing absorptions for cyclopropyl at 3010 cm^{-1} and 1030 cm^{-1} and absorptions for $-\text{CH}=\text{CH}_2$ at 3080 cm^{-1} , 1860 cm^{-1} , 1650 cm^{-1} , 990 cm^{-1} , and 930 cm^{-1} .⁸⁶

Dichloromethylenecyclopropane thus closely mimics the biradical cycloaddition behavior of 1122 in that both 1,2 adducts with butadiene and dimers are formed with "most stable biradical" orientation.

Dichloromethylenecyclopropane has olefinic destabilization in common with fluoroalkenes. Wiberg and Fenoglio find ring strain energies of 27.5 kcal/mole for cyclopropane, 41.0 kcal/mole for methylenecyclopropane, and 52.6 kcal/mole for cyclopropene (combustion).⁸⁷ That is, strain energy increases roughly 13 kcal/mole for each olefinic center introduced into a cyclopropane ring. In converting a methylenecyclopropane to a cyclopropane, 13 kcal/mole more energy is released than in a normal alkene to alkane conversion. This compares to roughly 16 kcal/mole destabilization energy in tetrafluoroethylene and 5 kcal/mole destabilization energy in 1122.⁸⁰

As a result of distortions caused by the cyclopropane ring the cyclopropyl olefinic carbon of dichloromethylenecyclopropane has a hybridization quite similar to that of $\text{sp}^3\text{ CF}_2$ groups in fluoroalkenes. Bennett points out that the olefinic carbon of a methylenecyclopropane is sp^3 hybridized regardless of whether bent bond or Walsh models are

86. K. Nakanishi, Infrared Absorption Spectroscopy, Holden-Day, Inc., San Francisco, 1962.

87. K. B. Wiberg and R. A. Fenoglio, J. Am. Chem. Soc., 90, 3395(1968).

considered.⁸⁸ This similarity of hybridization between fluoroalkenes and methylenecyclopropanes extends as far as their having unusually high $\nu_{C=C}$: vinylidene fluoride and 1122 have $\nu_{C=C}$ at 1730 cm^{-1} ,⁸⁹ 2-methymethylenecyclopropane at 1750 cm^{-1} ,⁹⁰ and ethylenecyclopropane at 1800 cm^{-1} .⁹⁰ The microwave spectrum of methylenecyclopropane, however, indicates a C=C bond length of 1.332 \AA and an olefinic H-C-H bond angle of 114.3° .⁹¹ These values do not compare at all well with those previously cited for vinylidene fluoride, the corresponding fluoroalkene. Apparently the hybridizational situation for methylenecyclopropanes and fluoroalkenes becomes increasingly dissimilar with distance from the F_2C and cyclopropyl olefinic carbons.

Hybridizational differences farther out in the system may be assigned to the one major difference between methylenecyclopropane (or dichloromethylenecyclopropane) and fluoroalkenes. The fluorines of a fluoroalkene are much more electron withdrawing than the carbons of a cyclopropane ring. This is doubly true since the methylene carbons of a cyclopropane ring are extending relatively electropositive sp^5 orbitals towards their olefinic carbon.⁸⁸ Hence olefinic destabilization and/or olefinic rehybridization alone seem sufficient to cause biradical reactivity in olefins.

88. W. A. Bennett, *J. Chem. Ed.*, 44, 17(1967).

89. L. J. Bellamy, *The Infra-red Spectra of Complex Molecules*, John Wiley and Sons, Inc., New York, 1960, p.42.

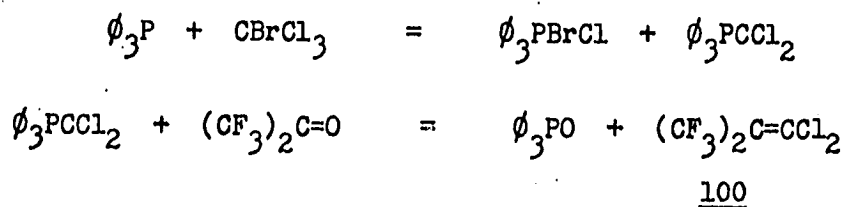
90. J. P. Chesick, *J. Am. Chem. Soc.*, 85, 2720(1963).

91. V. W. Laurie and W. M. Stigliani, *J. Am. Chem. Soc.*, 92, 1485(1970).

b. 1,1-bis(Trifluoromethyl)-2,2-dichloroethylene:

If indeed electron withdrawal plays no part in the biradical reactivity of fluoroalkenes, 1,1-bis(trifluoromethyl)-2,2-dichloroethylene 100 provides an interesting test by isolating the electron withdrawal of fluoroalkenes from their destabilization and perhaps their rehybridization. Clearly 1,1-bis(trifluoromethyl)-2,2-dichloroethylene has the required electron withdrawal since the Hammett σ_m^- value for trifluoromethyl is still larger than that for fluorine.⁷⁵ Previously given data of Patrick⁸⁰ indicate that, in contrast to fluorine, trifluoromethyl groups stabilize an olefin. It remains uncertain whether there is any hybridizational resemblance between 1,1-bis(trifluoromethyl)-2,2-dichloroethylene and fluoroalkenes such as 1,1-dichloro-2,2-difluoroethylene; for, if the steric size of the trifluoromethyl groups is not too large, electron withdrawal by $-\text{CF}_3$ should cause the $\text{CF}_3\text{-C-CF}_3$ angle to close with rehybridization of olefinic carbon towards sp^3 .⁷⁶

1,1-bis(Trifluoromethyl)-2,2-dichloroethylene is prepared by heating a bromotrichloromethane solution of triphenylphosphine with an excess of hexafluoroacetone in a sealed tube.^{92, 93} The volatile

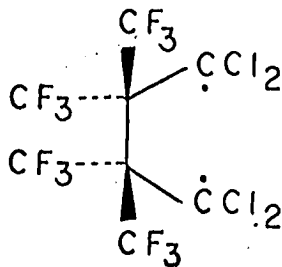


92. R. Rabinowitz and R. Marcus, *J. Am. Chem. Soc.*, **84**, 1312(1962).

93. For an earlier and tedious preparation: A. L. Henne, J. W. Shepard, and E. J. Young, *J. Am. Chem. Soc.*, **72**, 3577(1950).

product isolated by preparative vpc in 30% yield has a sharp (half height width 7 Hz) singlet in the ^{19}F nmr at 60 ϕ . The mass spectrum has a parent peak with exact mass 231.9275 (calc. 231.9281); $(P+4)/(P+2)/P = 0.1/0.64/1.0$ (calc. 0.1/0.65/1.0); base peak at mass 69 (CF_3^+); and additional peaks corresponding to loss of F, Cl, CF_3 , and CCl_2 . In the IR a strong $\nu_{\text{C}=\text{C}}$ at 1600 cm^{-1} was apparent. 1,1-bis(Trifluoromethyl)-2,2-dichloroethylene was shown to be distinct from $\text{CF}_3\text{ClC}=\text{CClCF}_3$ by IR and ^{19}F nmr comparison to a commercial cis, trans mixture (Peninsular Chemresearch, Gainesville, Florida).

1,1-bis(Trifluoromethyl)-2,2-dichloroethylene was recovered unchanged after heating to 250 $^\circ\text{C}$ in a sealed tube and was found not to cycloadd butadiene at temperatures as high as 250 $^\circ\text{C}$. The fact that 100 does not dimerize is hardly surprising on steric grounds since in the biradical shown below the two closest fluorines, even in the most favorable rotamers around the C- CF_3 bonds, are never farther than 1.35 \AA apart.⁹⁴ Steric effects, however, do not account for the



94. Estimated with Prentice-Hall Framework Molecular Models and a ruler. The nonbonded van der Waals' radius of fluorine is 1.35 \AA .

failure of 100 to cycloadd butadiene since models suggest that the known additions of 1122 to 2,4-hexadiene and 1,4-dichlorobutadiene are considerably more hindered.⁹⁴ Stabilization of C=C by the trifluoromethyl groups may explain the failure to see even Diels-Alder cycloaddition to butadiene. Nonetheless it remains that extreme electron withdrawal alone does not activate biradical reactivity. Combined with the observation that the absence of electron withdrawal in no way inhibits biradical reactivity, one concludes that olefinic destabilization and/or rehybridization are the primary source of biradical reactivity in fluoroalkenes.

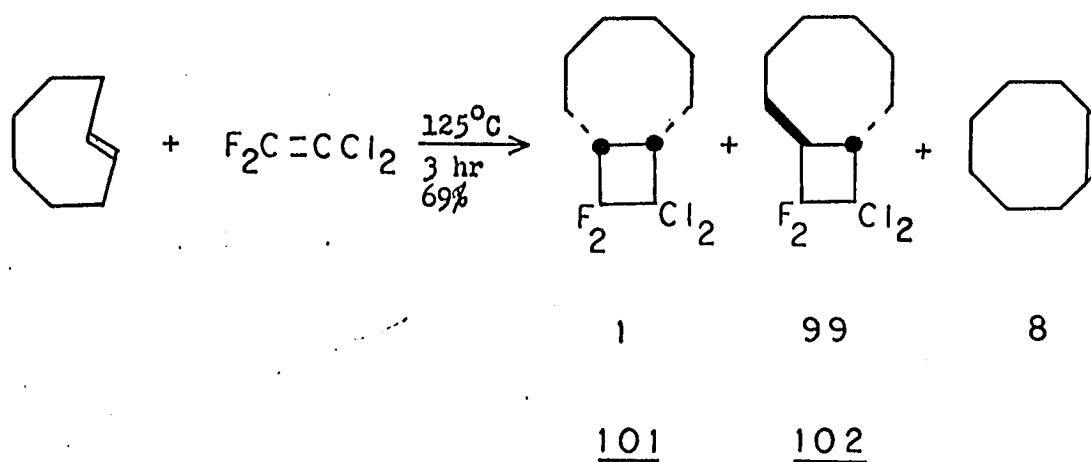
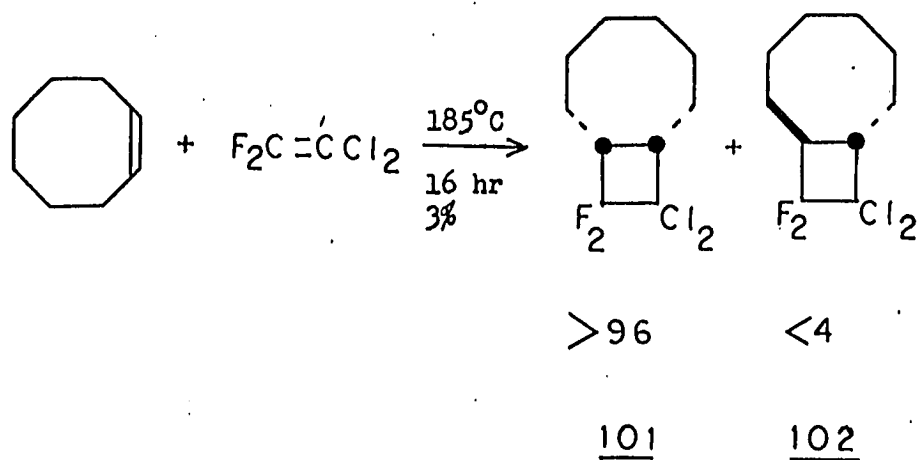
2. Effect of olefinic destabilization by C=C bond twisting

a. Cycloaddition of 1122 to trans-cyclooctene: The heat of hydrogenation of trans-cyclooctene is roughly 9 kcal/mole greater than that of cis-cyclooctene.⁹⁵ Use of models⁹⁴ clearly indicates that this apparent 9 kcal/mole of destabilization in trans-cyclooctene arises as a result of twisting about the C=C bond. Twisting about a C=C bond fortunately results in no rehybridization of olefinic carbons,⁹⁶ and study of the biradical reactivity of trans-cyclooctene will thus isolate the effect of olefinic destabilization from the previously complicating presence of olefinic rehybridization.

95. R. B. Turner and W. R. Meador, J. Am. Chem. Soc., 79, 4133(1957).

96. Only the π bond system is affected by rotation whereas the σ bond system retains its original hybridization, sp^2 . C. A. Coulson and E. T. Stewart, Chapt. 1: "Wave mechanics and the Alkene Bond" in ed. S. Patai, The Chemistry of Alkenes, Interscience Publishers, New York, 1964, p. 137.

The result of thermal cycloaddition of 1122 to cis- and trans-cyclooctene is summarized below,



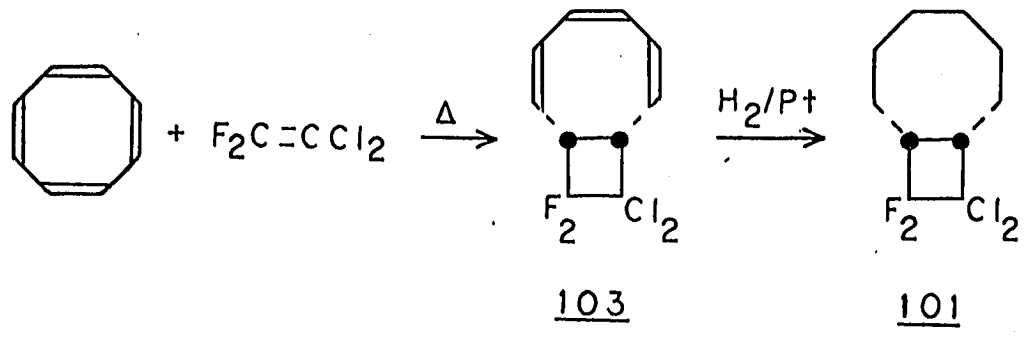
Heating 1122 with trans-cyclooctene for 3 hr at 125°C affords a 69% yield of 101 and 102, preparatively separable using a 20% Carbowax 20M vpc column. Their mass spectra confirm cross adduct structure: for 101 the parent peak mass is 242.0452 (calc. 242.0441) and $(P+2)/P = 0.63$ (calc. 0.65) whereas for 102 the parent peak mass is 242.0434 and $(P+2)/P = 0.64$. In both cases a major peak occurs at mass 110 (cyclooctene⁺).

The ¹⁹F nmr of both 101 and 102 are AB quartets on rapid sweep, $J_{AB} = 181$ Hz for 101 and $J_{AB} = 185$ Hz for 102. This AB quartet structure is characteristic of a geminal CF₂ group and assures that none of the less reactive 1212 contaminating 1122 has been carried along. The proton nmrs tend toward broad multiplets running from about 1-3 δ. Overlap between the bridgehead and methylene protons is sufficiently great to preclude meaningful integration.

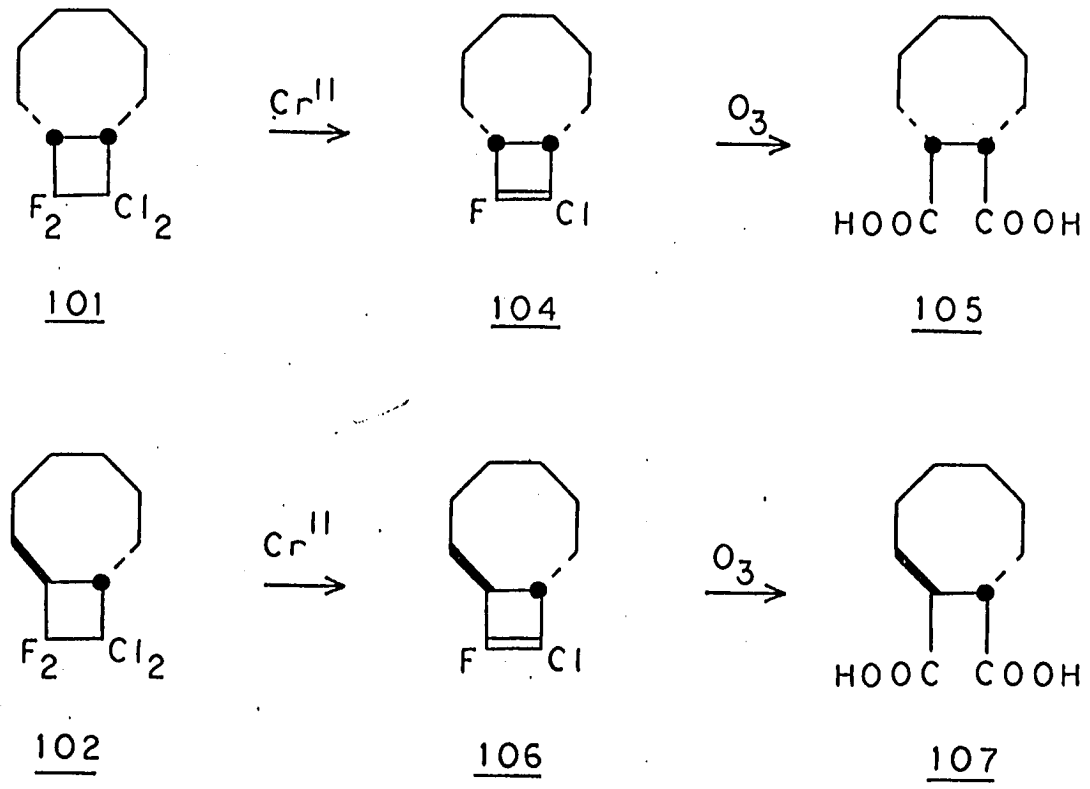
Synthesis, degradation, and an IR correlation were brought to bear on the configuration of the ring fusion in 101 and 102. Adduct 101 has a doublet in the 1400-1500 cm⁻¹ region of the IR that is characteristic of cis ring fused bicyclo(6.2.0)decanes whereas 102 has the singlet in the 1400-1500 cm⁻¹ region that is characteristic of trans ring fused bicyclo(6.2.0)decanes.⁹⁷ The known compound 103⁹⁸ was hydrogenated to give the cis ring fused adduct 101 presumably with retention of ring fusion configuration:

97. R. Montaigne and L. Ghosez, Angew. Chem. Internat. Ed. Eng., 7, 221(1968).

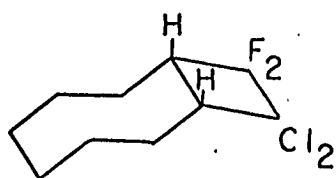
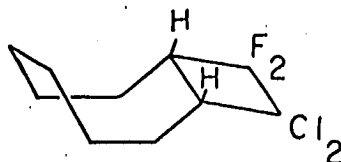
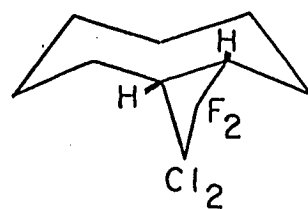
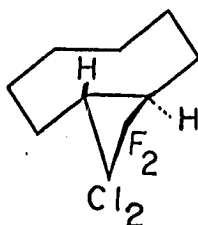
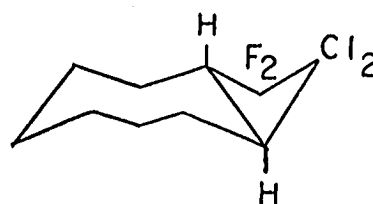
98. G. Schröder and Th. Martini, Angew. Chem. Internat. Ed. Eng., 6, 806(1967).



Adducts 101 and 102 were dehalogenated and then oxidized with ozone as illustrated below,



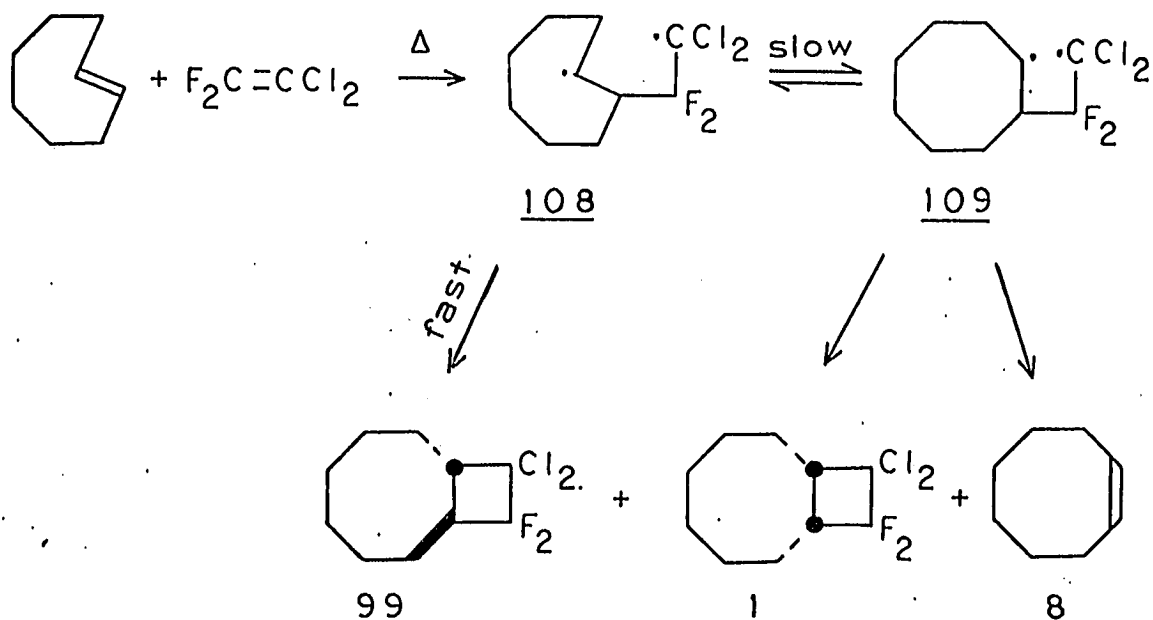
Coupling constants necessary for later structure assignments can be extracted from the first order ^{19}F nmr spectra of 101 and 102. Cyclooctyl systems are frequently visualized in chair, crown, or tub conformations.^{100, 101} These conformations are illustrated below for adducts 101 and 102.

101A101B101C102A102B

100. E. Eliel, Stereochemistry of Carbon Compounds, McGraw-Hill Book Co., Inc., New York, 1962, Chapt. 9.

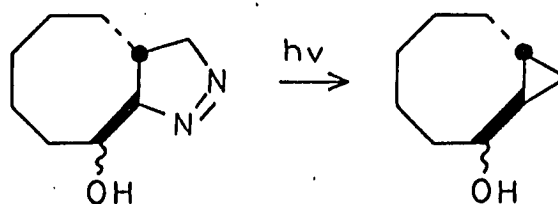
101. R. Montaigne, Dissertation for the Doctor of Science, Universite Catholique de Louvain, 1968.

The adducts 101 and 102 from trans-cyclooctene and 1122 appear stable to the reaction conditions. When heated alone at 125°C for 3 hr trans-cyclooctene does not isomerize to cis-cyclooctene in essential agreement with Cope and Pawson's report that optically active trans-cyclooctene has a 122 hr half life at 132.7°C .¹⁰² It is still quite possible, however, that the cis-cyclooctene formed on cycloaddition arises simply from thermal isomerization of trans-cyclooctene since the extent of thermal isomerization may depend critically on solvent and/or trace impurities; for, heating 50 μl of trans-cyclooctene in 0.5 g of pentane for 3 hr at 125°C results in 3% isomerization to cis-cyclooctene while some 7% isomerization is observed in acetonitrile. Thus, the origin of cis-cyclooctene in the scheme below must be viewed with extreme caution.

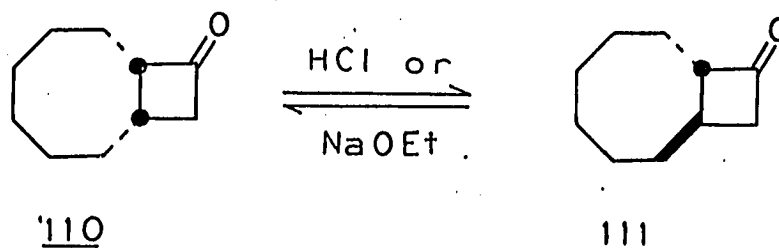


102. A. C. Cope and B. A. Pawson, J. Am. Chem. Soc., 87, 3649(1965).

At first the 99:1 predominance of trans ring fused adduct 102 seems quite surprising for a biradical cycloaddition in which free rotation is expected. Free rotation in cyclooctane rings may, however, be severely restricted as a result of the hydrogen-hydrogen repulsions known to occur in medium-sized rings.^{95, 100} Indeed such a failure of the cyclooctyl moiety to show loss of configuration in a biradical is not entirely unprecedented as, for example, in the photolysis of the azo compound below,¹⁰³

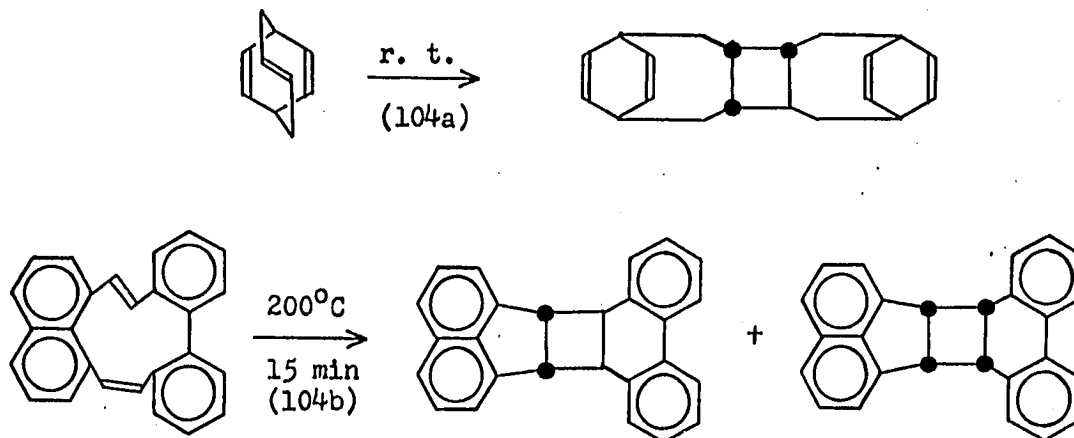


Furthermore, no particular driving force is to be associated with the conversion of biradical 108 into 109 analogous to that in the trans- to cis-cyclooctene conversion; for, Montaigne has found the equilibrium ratio between 110 and 111 to be roughly 1.¹⁰¹



103. K. B. Wiberg and A. de Meijere, Tetrahedron Lett., 59(1969).

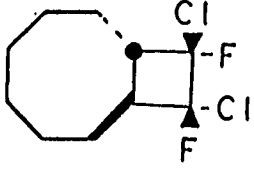
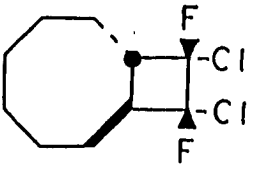
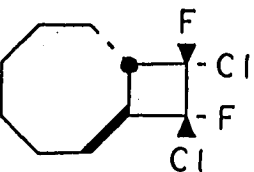
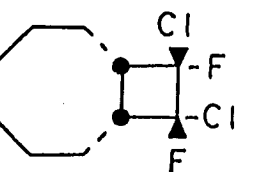
As an alternate possibility $\pi^2_s + \pi^2_a$ Woodward-Hoffmann allowed cycloaddition³⁴ could account for retained trans-cyclooctene configuration if 1122 is adding π^2_a . Such reactions are indeed known having been reported for compounds with trans strained bonds.¹⁰⁴



In this connection it should be noted that the cycloaddition of cis-cyclooctene to 1122 shows a similar retention of original cyclooctene configuration although the twisting of the C=C bond propitious for $\pi^2_s + \pi^2_a$ cycloaddition is absent. Fortunately altering the fluoroalkene moiety to 1212 will conclusively distinguish the two mechanisms. If the cycloaddition is $\pi^2_s + \pi^2_a$, cis- and trans-1212 will cycloadd with inversion of configuration. Whereas if the cycloaddition is biradical, cis- and trans-1212 will cycloadd with the scrambling of configuration that the cyclooctyl group is too congested to show.

104. a/ K. Kraft and G. Koltzenburg, Tetrahedron Lett., 4357(1967).
 b/ R. H. Mitchell and F. Sondheimer, Tetrahedron Lett., 2873(1968).

b. Cycloaddition of 1212 to trans-cyclooctene: Heating 1212 with trans-cyclooctene for 14 hr at 170°C produces four products, 112-115, in 51% yield that are preparatively separable using Carbowax 20M or TCEP vpc columns. Once isolated by vpc each of these four products gives a mass spectrum consistent with a 1:1 adduct structure.

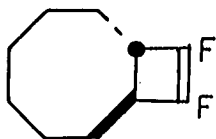
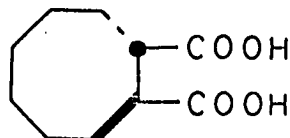
	Parent Peak Mass ^a	(P+2)/P ^b
	242.0439	0.65
	242.0444	0.67
	242.0433	0.60
	242.0466	0.65

a. calc. 242.0446

b. calc. 0.65

In all cases peaks at mass 207 (-Cl) and mass 110 (cyclooctene⁺) are evident.

To proceed any further ring fusion configurations must be known. In all cases the IR absorptions in the 1400-1500 cm⁻¹ region characteristic of cis- and trans-bicyclo(6.2.0)decane systems are consistent with the assigned structures. The Zn-Cr(II) dehalogenation of an 18% 112, 47% 113, 34% 114, and 1% 115 mixture affords 1% 106 and 99% 116 separable by vpc.

116106

The mass spectrum of 116 has a parent peak of mass 172.0166 (calc. 172.0163), (P+1)/P = 0.11 (calc. 0.11), and a peak at mass 110 (cyclooctene⁺). The IR shows strong $\nu_{C=C}$ at the high wavenumbers, 1770 cm⁻¹, associated with fluoroalkenes. Splitting on the part of the two bridgehead protons results in a symmetrical ¹⁹F nmr quartet. Ozonolysis followed by oxidation with hydrogen peroxide in formic acid yields a carboxylic acid with the melting point and IR spectrum previously found for 107. The trans configuration for acid 107 implies a similar trans ring fusion for its immediate precursor 116 and in turn for those adducts 112-114 originally present in significant

quantity (<1%). Given that all three possible trans fused adducts have thus been accounted for, the remaining trace adduct 115 must have a cis ring fusion by the process of elimination.

Now that the ring fusion geometry is known, ^{19}F nmr readily distinguishes cis halogen configurations from trans. With a trans ring fusion, the fluorines can be nonequivalent only if they are cis. Hence the trans ring fused adduct with two separate multiplets in its spectrum corresponds to structure 113. With a cis ring fusion the fluorines can be nonequivalent only if they are trans. Hence the cis ring fused adduct with two separate multiplets in its spectrum corresponds to 115. With a trans ring fusion the fluorines can be equivalent only if they are also trans. Hence the two trans ring fused adducts with single multiplets in their spectra must correspond to 112 and 114. Fine structure resulting from J_{HF} must be considered to distinguish further 112 from 114.

The bridgehead protons of 112 and 114 couple to the two fluorines giving an AA'XX' system. While a complete analysis of the ^{19}F nmr portion of these AA'XX' spectra requires resolution of all ten lines calculated by theory, partial analysis can still be carried out on more poorly resolved systems. The two strongest lines of the X part of an AA'XX' spectrum are generally located towards the outside of the multiplet and separated by $J_{\text{AX}} + J_{\text{AX}'}$. With J_{HF} values previously derived from first order analysis of 101 and 102, $J_{\text{AX}} + J_{\text{AX}'}$ values for 112 and 114 may be estimated. Comparison to

experimental values then serves to distinguish these two compounds: for 112 $J_{AX} + J_{AX'} = 19$ Hz (calc. 18 Hz) and for 114 $J_{AX} + J_{AX'} = 12$ Hz (calc. 8 Hz).

At this point a rather gratifying cis, trans ^{19}F nmr chemical shift correlation becomes apparent. If a fluorine and its vicinal bridgehead hydrogen are cis to one another, the fluorine in question will be said to be in the cis series; but, if a fluorine and its vicinal bridgehead hydrogen are trans to one another the fluorine in question will be said to be in the trans series. When defined in this manner all available examples have trans series fluorines appearing at higher field than the corresponding cis series fluorines as illustrated in Table IV. Note that compounds such as 115 can have both cis and trans series fluorines. Remarkably this correlation holds for both cis and trans ring fused systems. Dence and Roberts have reported a similar exo, endo chemical shift correlation for the norbornyl system.¹⁰⁵

The cycloaddition of 99% pure trans-1212, of 95% pure cis-1212, and of a 51:49 cis:-trans-1212 mixture to trans-cyclooctene was carried out at 170°C. The results are shown in Table V. Control experiments indicate that the adducts 112-115 as well as cis- and trans-1212 are stable to the reaction conditions. Any cis-cyclooctene formed by thermal isomerization of trans-cyclooctene does not react with 1212. Once again there is little rotation, 1-3%, in the

105. J. B. Dence and J. D. Roberts, J. Am. Chem. Soc., 91, 1542(1969).

TABLE IV
CYCLOADDITION OF TRANS-CYCLOOCTENE TO ClFC=CFCI

CONDITIONS	CONFIGURATION OF STARTING ClFC=CFCI	CONFIGURATION OF RECOVERED ClFC=CFCI	UNCORRECTED VPC TRACE AREA* OF ADDUCTS			
			112	113	114	115
172°C, 14h	99.3% <u>trans</u>	99.0% <u>trans</u>	27.2	20.2	49.2	3.4
172°C, 14h	95.4% <u>cis</u>	94.2% <u>cis</u>	10.2	67.0	21.4	1.4
172°C, 14h	51.3% <u>cis</u>	50.0% <u>cis</u>	17.8	46.9	33.8	1.5

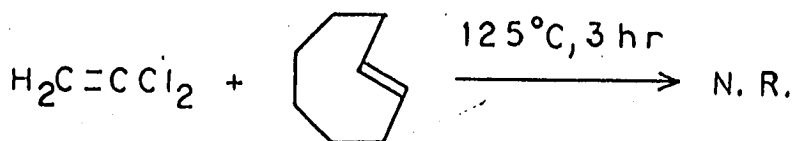
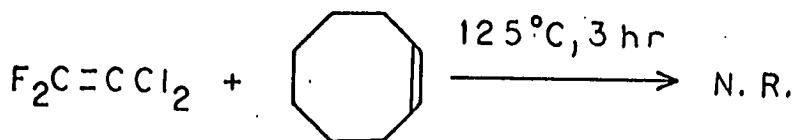
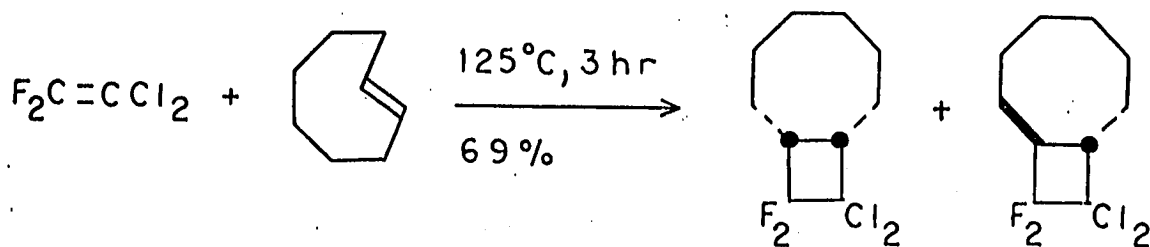
*10M X 1/8, 20% carbowax 20M, 60/80W, F&M Scientific Model 700 Vpc

cyclooctane ring itself. On the other hand roughly 20% rotation is observed in the trans-1212 moiety and 30% rotation in the cis-1212 moiety on addition to trans-cyclooctene. These values compare very well with those found for the addition of 1212 to cyclopentadiene. Apparently the additions of 1212 and hence also 1122 to trans-cyclooctene proceed by an entirely normal biradical mechanism. This is not to say, however, that the cyclooctyl moiety cannot show rotation; for example, Gassmann and Benecke report 22% rotation in the biradical cycloaddition of benzyne to trans-cyclooctene.¹⁰⁶ In this case one may hypothesize that the 80-90 kcal/mole of benzyne strain energy¹⁰⁷ leads to a highly energetic biradical in which rotation competes particularly successfully with ring closure (i. e. perhaps some of the strain energy in benzyne ends up as rotational excitation in the biradical intermediate). Nonetheless use of rotation in cis- and trans-cyclooctenes as a test for bifunctional intermediates is clearly hazardous as, for example, in the cycloaddition of dichloroketene to cyclooctene.⁹⁷

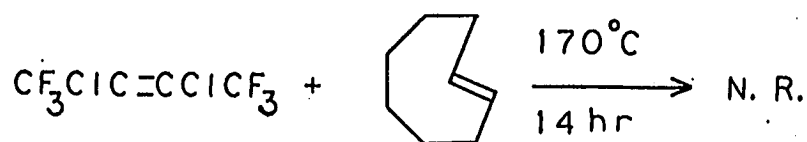
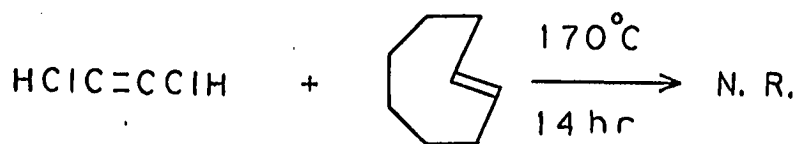
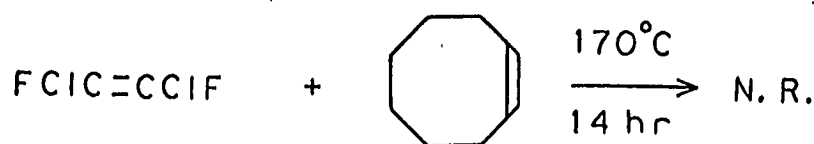
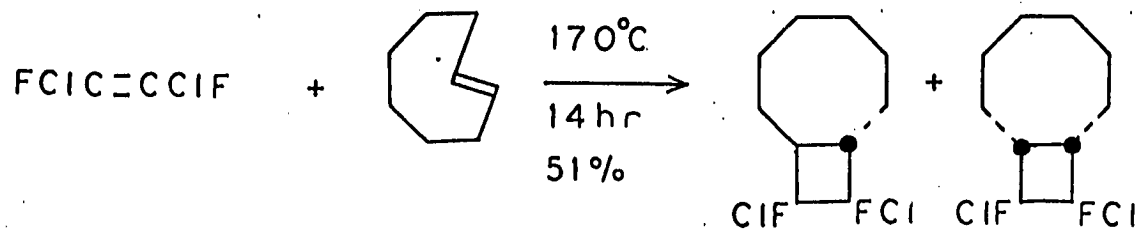
c. Implications of cyclooctene cycloadditions: Besides the successful cycloadditions of cis- and trans-cyclooctene just described a number of less successful cycloadditions are also listed below.

106. P. G. Gassmann and H. P. Benecke, Tetrahedron Lett., 1089(1969). Benzyne prepared from decomposition benzenediazonium-2-carboxylate. Therefore the reaction was most likely run in the 0-60°C range (ref. 107, p. 74) which is a considerably lower temperature than that used for our fluoroalkene cycloadditions.

107. R. W. Hoffmann, Dehydrobenzyne and Cycloalkynes, Academic Press, New York, 1967, p.268.

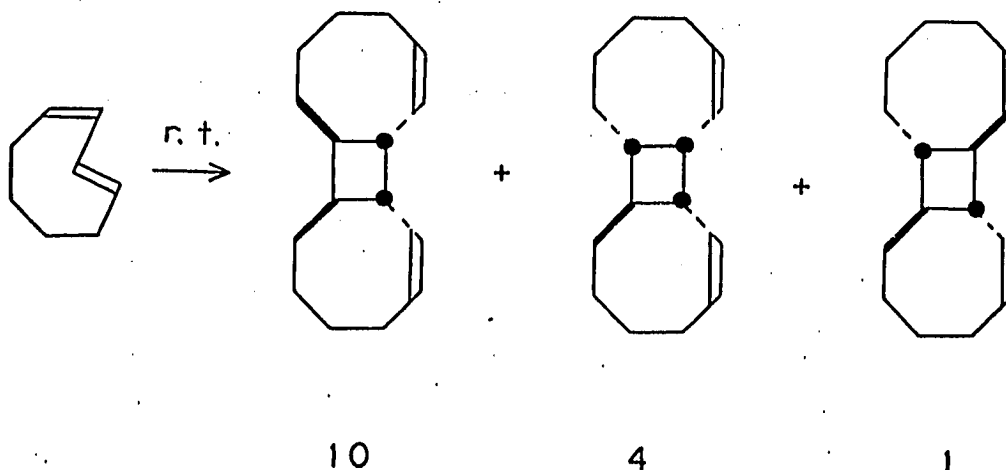


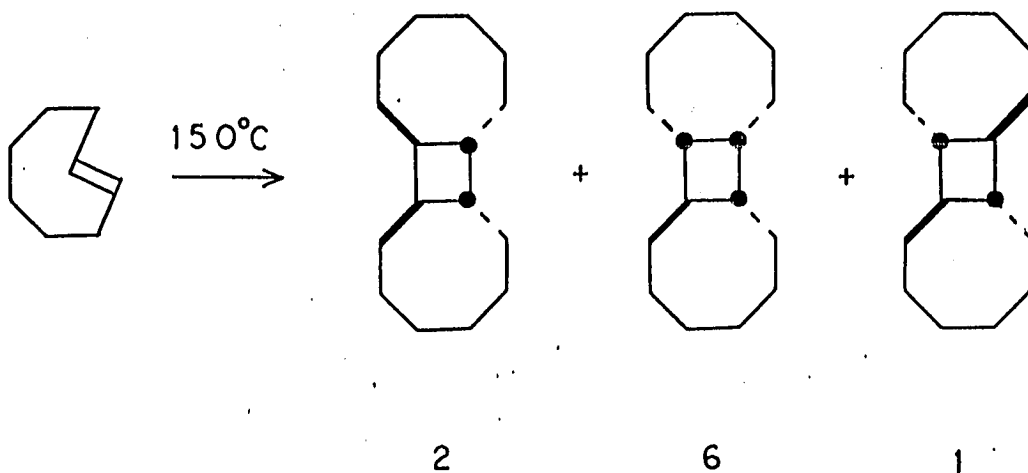
trans-Cyclooctene readily cycloadds 1,1,2,2-tetrachloroethene. But if the strain is removed from either of the reactive partners by replacing the trans-cyclooctene by cis-cyclooctene or by replacing the fluorines in 1,1,2,2-tetrachloroethene by hydrogen, the reaction fails to go under the original conditions.



trans-Cyclooctene readily cycloadds 1212. But if the strain is removed from either of the reactive partners by replacing the trans-cyclooctene by cis-cyclooctene or by replacing the fluorines of 1212 by hydrogen or trifluoromethyl, the reaction fails to go under identical conditions.

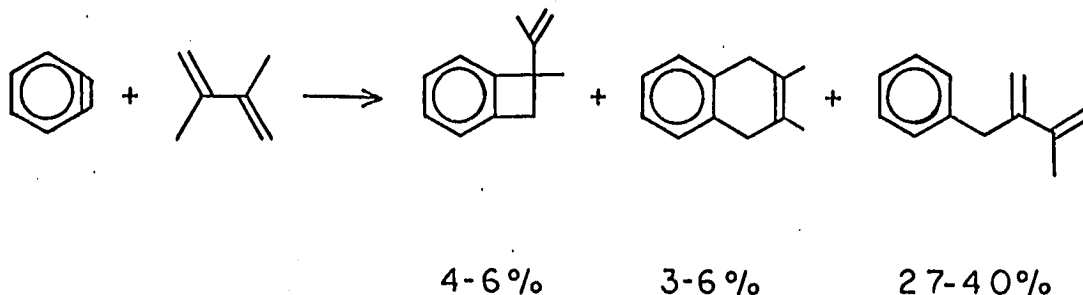
Clearly olefinic destabilization has a direct activating effect on biradical reactivity and appears to be a necessary condition. Nonetheless it is still uncertain whether olefinic rehybridization also is a necessary condition for biradical reactivity; for, while trans-cyclooctene is not rehybridized as are fluoroalkenes, all successful reactions cited above still include a rehybridized fluoroalkene as one of the reactant pair. This ambiguity is resolved by a recent report^{28c} of biradical reactivity between two trans-cyclooctenes:





In fact biradical reactivity has been reported for destabilized alkenes that encompass a whole spectrum of hybridizational states.^{105, 108} Benzynes, for example, can cycloadd both 1,2 and 1,4 to conjugated 1,3-butadienes much as do fluoroalkenes,^{108e}

-
108. a/ P. G. Gassmann, H. P. Benecke, and T. J. Murphy, Tetrahedron Lett., 1649(1969). b/ J. S. McConaghy, Jr., and J. J. Bloomfield, Tetrahedron Lett., 3719(1969). c/ M. Jones, Jr., and R. H. Levin, Tetrahedron Lett., 5593(1968). d/ A. M. Braun, J. Org. Chem., 35, 1208(1970). e/ G. Wittig and H. Dürr, Liebigs Ann. Chem., 672, 55(1964). f/ H. H. Wassermann, A. J. Solodar, and L. S. Keller, Tetrahedron Lett., 5597(1968). g/ I. Tabushi, R. Oda, and K. Okazaki, Tetrahedron Lett., 3743(1968). h/ H. E. Simmons, J. Am. Chem. Soc., 83, 1657(1961). i/ T. Miwa, M. Kata, and T. Tamano, Tetrahedron Lett., 1761(1969). j/ I. Tabushi, K. Okazaki, and R. Oda, Tetrahedron, 25, 4401(1969). k/ C. D. Campbell and C. W. Rees, Chem. Commun., 192(1965). l/ J. R. Wiseman and J. A. Chong, J. Am. Chem. Soc., 91, 7775(1969). m/ B. C. Anderson, J. Org. Chem., 27, 2720(1962).



Since biradical reactivity is seen in destabilized olefins with normal hybridization (trans-cyclooctenes), fluoroalkene hybridization, and benzyne hybridization, one concludes that olefinic destabilization is not only a necessary but also a sufficient condition for biradical reactivity quite independent of any rehybridization effects.

d. Biradical reactivity of trans-cyclooctene relative to fluoroalkenes: In later arguments a measure of the biradical reactivity of trans-cyclooctene relative to that of fluoroalkenes will be needed. Hydrogenation energies have already established that trans-cyclooctene is strained 9 kcal/mole relative to cis-cyclooctene. Comparison of the hydrogenation energy of trans-cyclooctene to that of normal alkenes, however, reveals the remarkable fact that compared to ethylene (the standard used for fluoroalkene destabilization energies⁸⁰) trans-cyclooctene is not destabilized at all. The two factors contributing to this are 1/ the presence of two stabilizing alkyl groups in trans-cyclooctene and 2/ the hydrogen-hydrogen repulsions

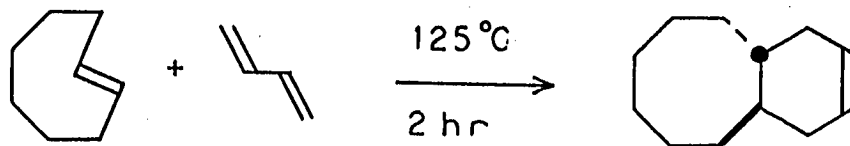
introduced in hydrogenation of medium-sized rings.⁹⁵ If this analysis is correct, the absolute biradical reactivity of trans-cyclooctene should be on the order of ethylene's and exclusively 1,4 addition should occur with butadiene.⁴⁴

Alkene	Heat of Hydrogenation	Conditions
<u>trans</u> -cyclooctene	-32.24 kcal/mole	25°C, HOAc (95)
<u>cis</u> -cyclooctene	-22.98 kcal/mole	25°C, HOAc (95)
cyclohexene	-27.10 kcal/mole	25°C, HOAc (95)
ethylene	-32.78 kcal/mole	25°C, gas (109)

When trans-cyclooctene is heated with butadiene at 125°C for 2 hr, there is obtained a colorless oil which appears to be a single material on Carbowax 20M and TCEP vpc columns. The mass spectrum is correct for the expected 1:1 adduct with exact mass 164.156 (calc. 164.157), (P+2)/P = 0.13 (calc. 0.13), and additional peaks at mass 110 (cyclooctene⁺) and mass 54 (butadiene⁺). The nmr integrates for 2.1 vinyl protons and 18 alkyl protons which is correct for a (2+4) adduct but not for a (2+2) adduct. Since the reaction is a (2+4) Diels-Alder cycloaddition, it may be assumed that the reaction went with retention of configuration requiring the product to have a trans ring fusion.¹¹⁰ We may thus write,

109. F. D. Rossini, J. Res. Nat. Bur. Stand., 17, 629(1936).

110. J. Shulman, unpublished results, Harvard U., 1970. As an example of such a trans ring fusion arising on a Diels-Alder reaction of trans-cyclooctene, Shulman has found that optically active trans-cyclooctene gives an optically active Diels-Alder adduct with 1,3-diphenylisobenzofuran.



Hence the intrinsic biradical reactivity of trans-cyclooctene approximates that of ethylene. This in no way alters our previous conclusions as to the enhancement of biradical reactivity by olefinic destabilization (destabilization being after all simply a matter of relative energies.)

Under the reaction conditions, 125°C for 2 hr, the reaction proceeds 98 to 99% to completion with little if any formation of cis-cyclooctene. Controls indicate that cis-cyclooctene forms no butadiene adduct under these conditions. Quite similarly 1122 proceeds 98 to 99% to completion with trans-cyclooctene in 3 hr at 125°C but with the formation of 8% cis-cyclooctene. This supports our previous assertion that the cis-cyclooctene in the 1122 cycloaddition arises by way of reverse biradical formation.

3. Acceleration of (2+2) relative to (2+4) cycloaddition by olefinic destabilization

a. Hammond Postulate argument: Fluoroalkene destabilization is responsible for biradical reactivity in that it apparently lowers the activation energy more for biradical cycloaddition than for competing Diels-Alder cycloaddition (see above, section II. A.) Use of the Hammond Postulate¹¹¹ rationalizes the greater effect that olefinic

111. G. S. Hammond, J. Am. Chem. Soc., 77, 334(1955).

destabilization has on biradical reactivity. In Figure V reaction profiles are shown for competing biradical (2+2) and concerted (2+4) paths. Both paths are expected to be kinetically controlled. For example, concerted (2+4) Diels-Alder cycloaddition normally gives the thermodynamically less favored endo adduct first and then the thermodynamically favored exo adducts only after prolonged heating and equilibration.^{19g} Clearly (2+2) cycloaddition is also kinetically controlled since vinylcyclobutanes are formed in preference to cyclohexenes that have 25 kcal/mole less ring strain energy¹¹² -- the driving force behind rearrangement of vinylcyclobutanes to cyclohexenes.¹¹³ As a consequence of kinetic control the relative rates of (2+2) and (2+4) cycloaddition shall reflect only the relative heights of their respective energy barriers ΔF_{12}^\ddagger and ΔF_{14}^\ddagger rather than any ultimate stability of their final products 94 and 96.

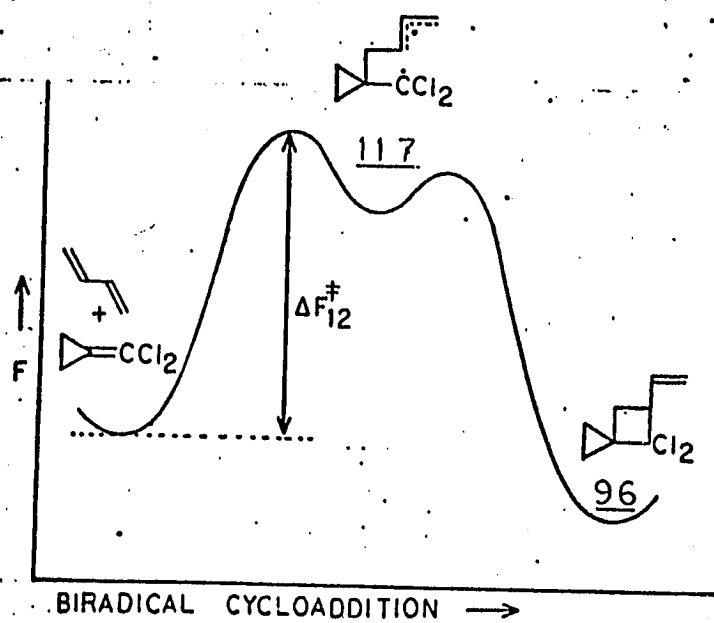
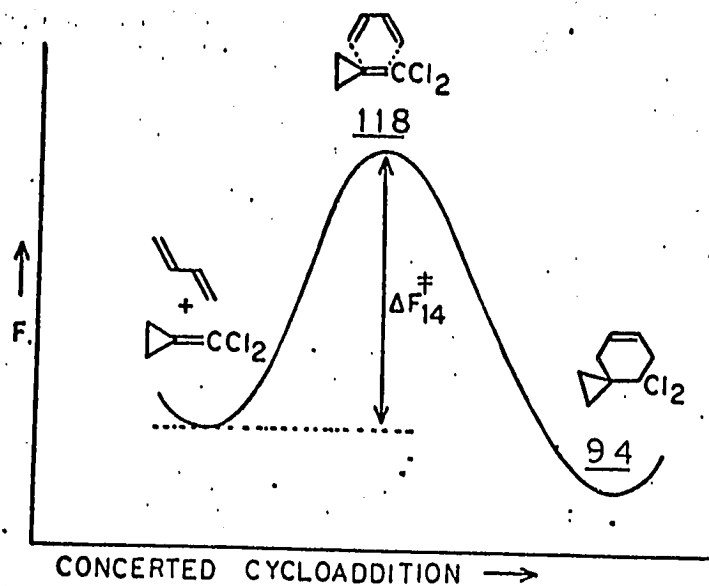
Let us now consider the biradical cycloaddition in detail. Dichloromethylenecyclopropane and butadiene give a biradical intermediate 117 corresponding to an energy valley. According to the Hammond Postulate two successive species along the reaction coordinate with similar energies have similar structures and hence the transition state corresponding to ΔF_{12}^\ddagger has a structure very much like that of the intermediate 117. If this is the case, then the

112. H. A. Skinner and G. Pilcher, Quart. Rev., 17, 264(1966).

113. a/ J. J. Drysdale, U. S. 2,861,095 (1958); C. A., 53, 9102a(1959).
 b/ G. S. Hammond and C. D. DeBoer, J. Am. Chem. Soc., 86, 899(1964).
 c/ D. J. Trecker and J. P. Henry, J. Am. Chem. Soc., 86, 902(1964).

FIGURE V

ENERGY PROFILES FOR COMPETING BIRADICAL
AND CONCERTED MODES OF CYCLOADDITION

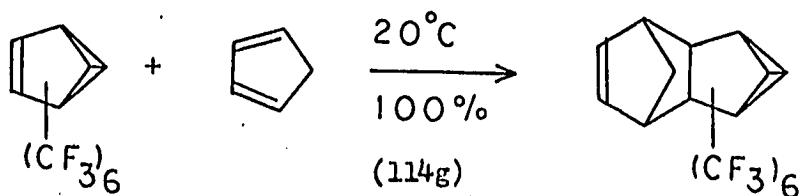
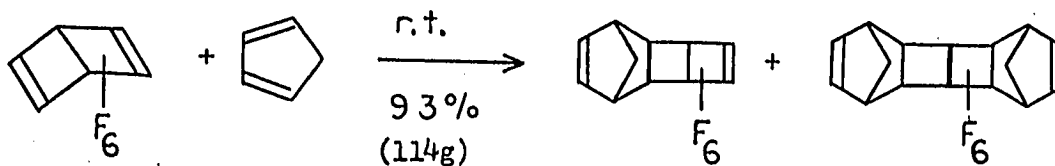
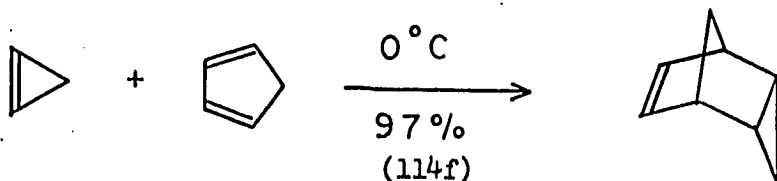


methylenecyclopropane has been essentially entirely converted to a methylcyclopropane in the transition state. This allows the transition state to take full advantage of the relief of strain energy available in a methylenecyclopropane to methylcyclopropane conversion. In other words the energy barrier to biradical cycloaddition has been lowered by roughly 13 kcal/mole, the full value of olefinic destabilization.

Let us now compare the competing Diels-Alder cycloaddition of dichloromethylenecyclopropane to butadiene. The transition state 118 for Diels-Alder cycloaddition is not similar in energy to either reactants or products and hence most likely intermediate in structure between starting reactants and final products. Conversion of the methylenecyclopropane to a methylcyclopropane will have run only part way in the transition state and advantage will be taken of only part of the total relief in strain energy that is ultimately to occur. Since in contrast biradical cycloaddition takes full advantage of the relief of strain energy, ΔF_{12}^\ddagger is lowered relative to ΔF_{14}^\ddagger allowing the rate of biradical cycloaddition to overtake that of Diels-Alder cycloaddition.

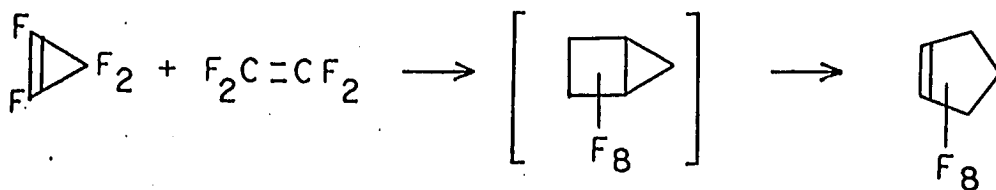
This does not mean that large olefinic destabilization energies indiscriminately lead to biradical behavior. As a class small rings with cis endocyclic bonds prefer to cycloadd in the Diels-Alder manner.

This includes cyclopropenes,^{114a-f} Dewar benzenes,^{114g} and benzvalenes.^{114g}



114. a/ M. A. Battiste, J. Am. Chem. Soc., **85**, 2175(1963). b/ D. C. Law and S. W. Toby, J. Am. Chem. Soc., **90**, 2376(1968). c/ G. L. Closs, L. E. Closs, and W. A. Boll, J. Am. Chem. Soc., **85**, 3796 (1963). d/ P. B. Sargeant and C. G. Krespan, J. Am. Chem. Soc., **91**, 415(1969). e/ M. A. Battiste, Tetrahedron Lett., 3795(1964). f/ K. B. Wiberg and W. J. Bartley, J. Am. Chem. Soc., **82**, 6375 (1960). g/ M. G. Barlow, R. N. Haszeldine, and R. Hubbard, Chem. Commun., 301(1969).

These results, however, are most readily rationalized in terms of reaction profiles such as those we have already discussed for dichloromethylene-cyclopropane and butadiene. The cycloaddition of cyclopropene to cyclopentadiene serves as a convenient example since the strain energies are known. In the case of biradical addition the transition state is of the form 119 in which 13 kcal/mole of strain energy is being efficiently utilized in conversion of a cyclopropane to a methylenecyclopropane. In the case of the Diels-Alder cycloaddition the transition state is of the form 120 in which 26 kcal/mole of strain energy is being inefficiently utilized in conversion of a cyclopropene to a cyclopropane. The inefficient use of twice as much strain energy in the case of the Diels-Alder reaction is sufficient to overwhelm any tendency towards biradical cycloaddition. It should be noted that the proposed utilization of only 13 kcal/mole of strain energy in 119 reflects the unfavorability of cyclopropyl radicals. Indeed if cyclopropyl radicals were not so unfavorable, cyclopropenes would probably be excellent biradical reagents. Only when there is no alternative Diels-Alder path (as in the addition of perfluorocyclopropene to tetrafluoroethylene shown below) will such compounds show the biradical reactivity expected on the basis of their destabilization.^{114d}

119120

Use of the Hammond Postulate thus conveniently rationalizes olefinic destabilization as the primary source of biradical reactivity in fluoroalkenes. This model also carries implications that are subject to experimental verification.

b. Supporting data for the Hammond Postulate interpretation of biradical reactivity: If the interpretation of biradical reactivity according to the Hammond Postulate is correct, the conversion of unsaturated centers to saturated centers should proceed much farther in the transition state for a biradical (2+2) cycloaddition than for a concerted (2+4) cycloaddition. Since secondary deuterium isotope effects are sensitive to such hybridizational changes, a number have been gathered in Figure VI for Diels-Alder and retro Diels-Alder reactions.^{115a-d} Inasmuch as such secondary α -deuterium isotope effects are normally of the order of 1.12,¹¹⁶ the small values obtained for the Diels-Alder and retro Diels-Alder reactions have been interpreted in terms of rather slight sp^2 to sp^3 or sp^3 to sp^2 hybridizational changes in leading up to the transition state.^{115a, b, d, 117} Using a Hammett ρ^- analysis of Diels-Alder cycloaddition, Charton also concludes that only slight hybridizational changes have occurred at the transition state.^{22g}

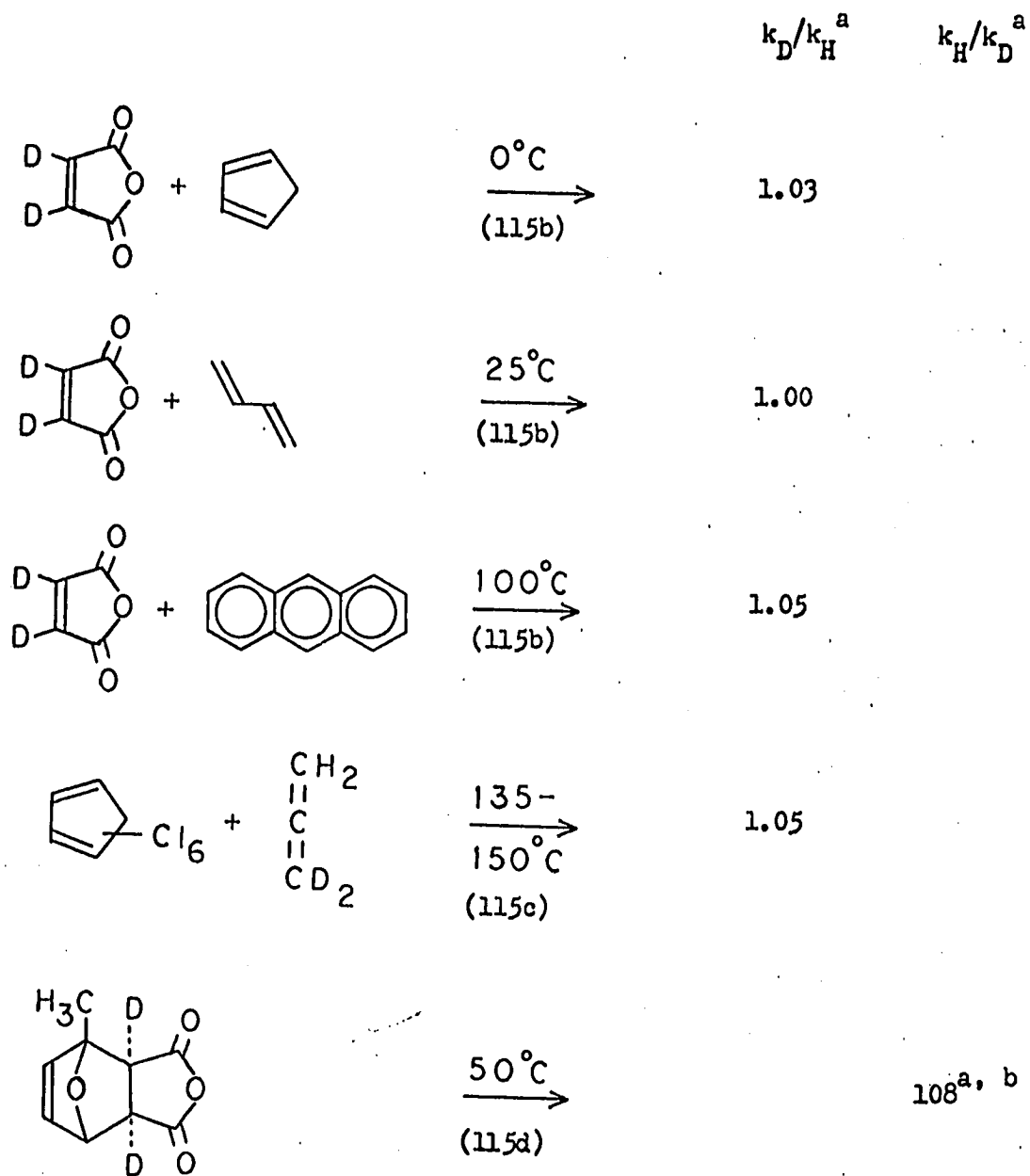
115. a/ S. Seltzer, Adv. in Alicyclic Chem., 2, 1(1968). b/ D. E. van Sickle and J. O. Rodin, J. Am. Chem. Soc., 86, 3091(1964). c/ W. R. Dolbier, Jr., and S.-H. Dai, J. Am. Chem. Soc., 90, 5028 (1968). d S. Seltzer, J. Am. Chem. Soc., 87, 1534(1965). e/ For a qualitative discussion of the origin of deuterium isotope effects see: A. Streitwieser, Solvolytic Displacement Reactions, McGraw Hill Book Co., Inc., New York, 1962, p. 99-101.

116. S. Seltzer, J. Am. Chem. Soc., 83, 2625(1961).

117. P. Brown and R. C. Cookson, Tetrahedron, 21, 1993(1965).

Figure VI

Deuterium Isotope Effects



a. Isotope effect per single deuterium, for calculation see see ref. 115b footnote in Table II

b. Assuming equal contributions from both deuteriums

Unfortunately analogous isotopic studies have not been carried out for biradical 1,2 cycloaddition. However, a deuterium isotope effect of $k_D/k_H = 1.13$ has been observed in the cycloaddition of diphenylketene to cyclohexene-1-D.^{118a} This illustrates that cycloadditions can indeed show a full secondary isotope effect and hence a full hybridizational change. Furthermore, cycloadditions of diphenylketene generally involve considerable asymmetry in the rate of bond formation¹¹⁹ which, according to the isotope effect, requires considerable rehybridization at a single carbon rather than slight changes at two carbons. Thus, consistent with our model based on the Hammond Postulate, Diels-Alder cycloaddition seems to proceed with small hybridizational changes at the transition state whereas asymmetric cycloaddition (resembling biradical) is found to involve considerably greater hybridizational changes.

According to the model developed thus far the rates for 1,2 biradical cycloaddition, k_{12} , and for concerted 1,4 cycloaddition, k_{14} , may be expressed by equations of the form

$$k_{12} = Ae^{-E_{12}/RT}$$

$$k_{14} = Ae^{-E_{14}/RT}$$

-
118. a/ T. J. Katz and R. Dessau, J. Am. Chem. Soc., 85, 2172(1963).
 b/ Admittedly isotope effects in ketene cycloadditions are rather poorly understood. In the addition of diphenylketene to styrene Baldwin reports $k_H/k_D = 0.91$ for β -deuterated styrene and $k_H/k_D = 1.23$ for α -deuterated styrene. J. E. Baldwin and J. A. Kapecki, J. Am. Chem. Soc., 91, 3106(1969).
119. a/ R. Huisgen and L. A. Feiler, Chem. Ber., 102, 3391(1969).
 b/ R. Huisgen, L. A. Feiler, and P. Otto, Chem. Ber., 102, 3444, 3405(1969). c/ R. Huisgen, L. A. Feiler, and G. Binsch, Chem. Ber., 102, 3460(1969).

Presumably rate variations derive almost exclusively from changes in E_{12} and E_{14} effected by olefinic destabilizing and electron delocalizing groups. Relative k_{12} and k_{14} values are relisted below,

Relative Rates of 1,2 and 1,4 Addition¹⁴
to Butadiene at 212°C

Dienophile	k_{12}	k_{14}
$H_2C=CH_2$	10^{-7}	10^{-3}
$H_2C=CF_2$	10^{-5}	10^{-4}
$HFC=CF_2$	10^{-3}	10^{-4}
$F_2C=CCl_2$	1	10^{-2}

With a normal dienophile such as ethylene the rate for 1,2 cycloaddition lags roughly 10^{-4} behind the competing 1,4 cycloaddition. At 212°C this corresponds to $E_{12} - E_{14} = 8.84$ kcal/mole. At first this difference may seem rather small compared to the 10-20 kcal/mole usually thought to separate allowed from forbidden Woodward-Hoffmann processes.¹²⁰ There are two reasons, however, why the observed energy difference should be considerably less than 10-20 kcal/mole.

120. The value of 10-20 kcal/mole cited is actually that for electrocyclic reactions rather than for cycloadditions. a/ A. Dahmen and R. Huisgen, Tetrahedron Lett., 1465(1969). b/ J. I. Brauman and D. M. Golden, J. Am. Chem. Soc., 90, 1920(1968). c/ E. C. Lupton, Jr., Tetrahedron Lett., 4209(1968). d/ G. A. Doorakian and H. H. Freedman, J. Am. Chem. Soc., 90, 5310(1968).

First the allylic resonance in the biradical (from ethylene plus butadiene) has already affected E_{12} much in the same manner as would have olefinic destabilization. Secondly, E_{12} is lowered relative to E_{14} by 2-3 kcal/mole since the biradical cycloaddition goes with either *s-cis* or *s-trans* butadiene but the Diels-Alder reaction only with higher energy *s-cis* butadiene.^{53, 121} Changing ethylene for 1122 increases the rate of 1,2 addition by 10^7 , corresponding to a lowering of E_{12} by 15.5 kcal/mole at 212°C. This 15.5 kcal/mole is probably within experimental error of the 13 kcal/mole of strain and resonance energy (see Figure VII) available in biradical intermediates from 1122 suggesting that the observed rate accelerations are not unreasonable on the basis of the energies available. Assuming that such close correlation between acceleration and strain energy is not simply fortuitous, it would then seem that the utilization of strain energy in biradical cycloaddition is as efficient as implied earlier in the Hammond Postulate argument. Furthermore the utilization strain energy in the competing Diels-Alder cycloaddition seems to be considerably less efficient; for, the tenfold Diels-Alder rate increase in going from ethylene to 1122 corresponds to lowering E_{14} by just 2.2 kcal/mole.

121. B. Eisler and A. Wassermann, J. Chem. Soc., 979(1953).

This method of treating biradical reactivity is semiquantitative at best since rather marginal success is had in predicting relative orders of biradical reactivity. Some of the failure is probably to be associated with (1) the diverse species considered, (2) the assumption that destabilization and delocalization energies contribute equally effectively, and (3) the assumption that the utilization of these energies is equally efficient from one reactant pair to another. In Figure VII a number of alkenes are rated in their experimental biradical reactivity as

strong: show occasional 1,2 cycloaddition to s-cis dienes

intermediate: show 1,2 addition only to s-trans dienes

weak: show significant 1,2 addition only with other alkenes

In Figure VII there is some uncertainty as to the position for butadiene. The stabilization of the C=C bonds in butadiene was estimated at 6 kcal/mole by comparing the heat of hydrogenation of butadiene 1-butene (-26.15 kcal/mole¹²²) to the heat of hydrogenation of ethylene (-32.78 kcal/mole¹⁰⁹). This 6 kcal/mole of stabilization energy is balanced against a large allylic delocalization energy in the biradical intermediate of 10 to 25 kcal/mole (Figure VII footnote d). More success is had in accounting for the failure of chloroethylenes such as trichloroethylene to show biradical behavior. In a biradical the CCl₂ group could afford 8 kcal/mole^{2b} of electron delocalization

122. E. J. Prosen, F. W. Maron, and F. D. Rossini, J. Res. Nat. Bur. Std., 46, 106(1951).

energy. This delocalization energy is comparable to many fluoroalkene destabilization energies. Chloroalkenes, however, do not show biradical reactivity on account of a compensating olefinic stabilization energy,

Compound	Heat of Cl ₂ Addition (kcal/mole) ¹²⁴		Apparent Stabilization (kcal/mole) ^b
	Calc. ^a	Expt. ^a	
H ₂ C=CH ₂	-43.3	-43.8	0
HClC=CH ₂	-43.3	-----	0
<u>cis</u> -ClHC=CHCl	-38.1	-37.8	6
Cl ₂ C=CHCl	-33.3	-34	10
Cl ₂ C=CCl ₂	-31.8	-32	12

a. gas phase at 25°C

b. relative to ethylene

124. F. W. Kirkbride, J. Appl. Chem. (London), 6, 11(1956).

III. Experimental

The following instruments and services were used,

^1H nmr	:	Varian T-60 Varian A-60 Varian HA-100
^{19}F nmr	:	Varian HR-60 at 56.4 MHz Varian HA-100 at 94.1 MHz
Mass spectra	:	Associated Electrical Industries MS-9
IR spectra	:	Perkin-Elmer Model 137B Infracord Spectrophotometer
Vpc	:	Aerograph Autoprep Model A-700 F & M Scientific Model 300 F & M Scientific Model 609 F & M Scientific Model 700
Ozone	:	Welsbach Ozonator Model T-23
Elemental analysis	:	Galbraith Laboratories, Inc., Knoxville, Tenn.
M. W. polymer	:	Galbraith Laboratories, Inc., Knoxville, Tenn.

All ^{19}F nmr spectra were taken in the HR mode and reported as ϕ values.¹²⁵ Determination of coupling constants and chemical shifts for the ^{19}F nmr spectra employ audio-frequency sideband modulation introduced by an external oscillator in the case of the HR-60 and by an internal oscillator in the case of the HA-100. The ^{19}F coupling constants were generally reproducible to within ± 1 Hz. No attempt was made to run the ^{19}F nmr spectra at uniform concentration or to extrapolate chemical shifts to infinite dilution so that reproducibility of the reported shifts may be somewhat poorer than the precision of $\pm 1 \phi$ found when considering individual samples.

125. ϕ value: chemical shift of fluorine defined as parts per million upfield from the internal reference CFCl_3 . G. Fillipovich and G. V. D. Tiers, J. Phys. Chem., **63**, 761(1959).

The following notation has been used to describe vpc columns,

P : Chromosorb P solid support
 W : Chromosorb W solid support
 AW : acid washed solid support
 DMCS : solid support treated with dimethyldichlorosilane
 DIDP : diisodecyl phthalate
 TCEP : 1,2,3-tris(2-cyanoethoxy)propane

With this notation a 20% Carbowax 20M, 30/60W AW DMCS column would be understood to mean a vpc column that is packed with 20% by weight Carbowax 20M on 30 to 60 mesh Chromosorb W which has been acid washed and treated with dimethyldichlorosilane.

Although exact masses on the MS-9 frequently have an accuracy of 2 to 3 ppm, errors of the order of 20 to 30 ppm are not uncommon. Generally heavy atoms such as chlorine are detected by characteristic isotope patterns and/or large mass defects. Once the accurate masses for these atoms have been subtracted from the experimental parent peak mass, the empirical formula may then be found by comparing the remaining mass to Beynon and Williams' listing of the exact masses for all possible $C_wH_xN_yO_z$ combinations up to mass 500.¹²⁶

Melting points are uncorrected.

126. J. H. Beynon and A. E. Williams, Mass and Abundance Tables for Use in Mass Spectrometry, American Elsevier Publishing Co., Inc., New York, 1963.

In view of the fact that many procedures are highly repetitious, as for example the chromous ion dehalogenation of nearly 20 separate compounds, a representative rather than fully complete set of procedures is described below.

Preparative Scale Cycloaddition of cis- and trans-1212 to Cyclopentadiene. Roughly 23 g of pure 1212, 5.6 g of cyclopentadiene, and a trace of hydroquinone were sealed under nitrogen in a heavy wall Pyrex tube. After heating for 7 hr at 210°C, the tube was opened and the contents distilled. There was obtained 3.7 g of yellow semisolid adduct mixture, $b_{10} = 60-70^{\circ}\text{C}$. Final purification and separation of the adducts was effected with a 20% Carbowax 20M, 30/60W AW DMCS column. No products other than adducts were detected out to retention times 2.5 times as great as for the adducts themselves. With a 5% DMSO, 80/100 alumina column at 0°C, the starting 1212 analyzed as 53% trans and 47% cis as did the 13.8 g of recovered 1212 after reaction.

Thermal Cycloaddition of trans-1212 to Cyclopentadiene. 1,2-Dichloro-1,2-difluoroethylene from which the contaminating 1122 had been removed was separated into cis and trans isomers with a 7M X $\frac{1}{4}$ ", 5% DMSO on 80/100 alumina column at room temperature. Analysis on a 1.25M X 1/8", 5% DMSO, 80/100 alumina column at 0°C indicated the separated trans-1212 to be in fact 99% trans-1212 with 1% cis-1212 impurity.

0.5 g of this 99% pure trans-1212 was bulb-to-bulb distilled into a 5/16" O. D. 5/32" I. D. Pyrex tube. To this tube was added 0.15g of freshly distilled cyclopentadiene, and 0.02 g of hydroquinone. After sealing under nitrogen, the tube was heated in an oven at 180-95°C for 8 hr and then cooled and opened.

Bulb-to-bulb distillation at roughly 60 mm gave recovered 1212 which still analyzed as 99% trans-1212 and 1% cis-1212.

Bulb-to-bulb distillation at 0.1 to 0.2 mm with the aid of a heat gun produced a colorless oil which analyzed on a 10M X 1/8", 20% Carbowax 20M, 60/80W column as,

Adducts	Uncorrected Vpc Area ^{a, b, c, d}
Dicyclopentadienes	24.1 ± 0.2
<u>50</u>	0.2 ± 0.2
<u>51</u>	1.2 ± 0.2
<u>52</u>	1.0 ± 0.2
<u>53</u>	0.3 ± 0.3
<u>54</u> + <u>55</u>	96.7 ± 0.6
<u>56</u>	0.6 ± 0.2

- a. adjusted to a total 1212-cyclopentadiene cross adduct area of 100
- b. Indicated uncertainty is the difference between two separate integrations. If there was no significant difference a value of ± 0.2 was arbitrarily assigned.
- c. analysis with F & M Scientific Model 700
- d. Considerably more confidence is had in the relative magnitudes of the 1,2 adducts with respect to one another than with respect to the 1,4 adducts as a whole.

The percentages of 54 and 55 were obscured as a result of their identical retention times on the vpc. This problem was solved by hydrogenating 10 μ l of the adduct mixture in 0.1 ml of methanol with $\text{PtO}_2 \cdot n\text{H}_2\text{O}$ as catalyst. Analysis of the methanol solution on a 10M X 1/8", 20% Carbowax 20M, 60/80 column indicated the following distribution,

Hydrogenated Adduct	Uncorrected Vpc Area ^{a, b, c}
<u>57</u>	0.2 \pm 0.4 ^b
<u>58</u>	1.6 \pm 0.4 ^b
<u>59</u>	0.5 \pm 0.4
<u>61</u> + <u>62</u>	97.7 \pm 0.4
<u>60</u>	undetectable

- adjusted to a total cross adduct area of 100
- Heavy trailing on the part of a large excess of methanol makes these values very tenuous. Arbitrarily assigned \pm 0.4 found for the 1,2 adducts as a group between two separate integrations.
- analysis with an F & M Scientific Model 700

Since there was 0.0% of 60 in the hydrogenated mixture there must also have been 0.0% of its precursor 54 in the original adduct mixture.

Since 54 + 55 = 96.7 in the original adduct mixture, 55 = 96.7.

Thermal Cycloaddition of cis-1212 to Cyclopentadiene. 0.5 g of 96% pure cis-1212 (see above) was bulb-to-bulb distilled into a 5/16" O. D. 5/32" I. D. Pyrex tube. To this tube was added roughly

0.15 g of freshly distilled cyclopentadiene, and 0.02 g of hydroquinone. After sealing under nitrogen, the tube was heated in an oven (simultaneously with the trans-1212 cyclopentadiene run) at 180-95°C for 8 hr and then cooled and opened.

The opened tube was sealed in an all-glass system at roughly 60 mm. Bulb-to-bulb distillation gave recovered 1212 analyzing as 95% cis-1212 and 5% trans-1212.

The all-glass system including the original cycloaddition tube was resealed at 0.1-0.2 mm. Bulb-to-bulb distillation with the aid of a heat gun produced a colorless oil which analyzed on Carbowax 20M as,

Adduct	Uncorrected Vpc Area ^{a, b, c, d}
Dicyclopentadienes	24.2 ± 1.1
<u>50</u>	2.4 ± 0.2
<u>51</u>	0.9 ± 0.2
<u>52</u>	1.0 ± 0.2
<u>53</u>	1.7 ± 0.2
<u>54</u> + <u>55</u>	33.7 ± 1.0
<u>56</u>	60.3 ± 2.7

- adjusted to a total 1212-cyclopentadiene cross adduct area of 100
- Indicated uncertainty is the difference between two separate integrations. If there was no significant difference a value of ± 0.2 was arbitrarily assigned.
- analysis with F & M Scientific Model 700
- Considerably more confidence is had in the relative magnitudes of the 1,2 adducts with respect to one another than with respect to the 1,4 adducts.

Continuing with the analysis of the cis-1212 adduct mixture with cyclopentadiene, roughly 20 μ l of this mixture was hydrogenated in 0.1 ml of methanol overnight with $\text{PtO}_2 \cdot \text{nH}_2\text{O}$ as catalyst. Analysis of the methanol solution indicated the following product distribution,

Hydrogenated Adduct	Uncorrected Vpc Area ^{a, b, c}
<u>57</u>	1.2 \pm 0.2
<u>58</u>	1.7 \pm 0.2
<u>59</u>	1.2 \pm 0.2
<u>61</u> + <u>62</u>	68.0 \pm 0.4
<u>60</u>	27.9 \pm 0.6

- a. adjusted to a total cross adduct area of 100
 b. Indicated uncertainty is the difference between two separate integrations. If there was no significant difference a value of \pm 0.2 was arbitrarily assigned. The 1,2 adducts are quite uncertain since there was heavy trailing on the part of the methanol.
 c. analysis with F. & M Scientific Model 700

The percentages of adducts 60-62 must first be adjusted somewhat in order to fit the percentages of their precursors before hydrogenation: since 54-56 = 94% before hydrogenation, 60-62 must be changed from 95.9% down to 94%. After adjustment one has 60 = 27.3% and 61 + 62 = 66.7%. The precursor of 62, that is 56, is already known to make up 60.3% of the total adduct mixture and hence so does 62. Since 61 + 62 = 66.7%, 61 must equal the difference 66.7 - 60.3% = 6.4%.

The question may arise why if one could analyze for 1% impurities in the 1212, they were not removed by vpc. The 1212 purity was determined with an analytical column that gave considerably better resolution than the column used for preparative separation. A second

pass on this preparative column would have been impractical since 1212 is a gas at room temperature and inordinate amounts are lost on delivery to the vpc and in collection. Such losses can be afforded with unseparated 1212 but not with the relatively small amounts of vpc purified material. As it was, well over a month of continuous work on the vpc was required to separate all the cis- and trans- 1212 used for this thesis.

Thermal Stability of 1212-Cyclopentadiene Adducts 50-56.

a/ 1,2 Adduct stability: Roughly 0.5 g of 1212, 0.1 g of adducts, and 50 μ l of decalin were sealed in a Pyrex tube under nitrogen. The reaction mixture was analyzed on Carbowax 20M before and after heating for 8 hr at 210°C. Before heating the relative vpc trace areas were 38.5 decalin, 14.2 50, 21.5 51, 25.0 52, 0.6 53, and 0.2 54 + 55. On recovery after heating the mixture analyzed for 37.2 decalin, 13.6 50, 22.1 51, 26.6 52, 0.4 53, and 0.1 54 + 55.

b/ 1,4 Adduct stability: Roughly 67 mg of adducts in 0.5 ml of 1212 were heated at 225°C for 10 hr in a sealed tube under nitrogen. The mixture before heating analyzed as 0.9 50-53, 92.9 54 + 55, and 6.2 56. After heating the mixture analyzed as 0.6 50-53, 92.4 54 + 55, and 7.0 56. Roughly 37 mg of the starting adducts were recovered by preparative vpc with a Carbowax 20M column.

c/ Constancy of adduct distribution with time: Two identical Pyrex tubes were prepared each containing roughly 0.4 ml of 1212, 0.1 ml of dicyclopentadiene, and a trace of hydroquinone under nitrogen.

Both tubes were put into the same oven at 180-95°C. The first tube was extracted after 2 hr and 20 min and analyzed for 0.6 50, 0.8 51, 1.3 52, 0.7 53, 63.7 54 + 55, and 32.9 56. The second tube was extracted after 28 hr and 30 min and analyzed for 0.5 50, 0.6 51, 0.9 52, 0.7 53, 62.1 54 + 55, and 35.3 56.

Preparative Photosensitized Cycloaddition of 1212 to Cyclopentadiene.

Two Pyrex glass tubes were each filled with 50 g of pure 1212, 2.5 g of cyclopentadiene, and 2.5 g of 2-acetonaphthone. After sealing under nitrogen the tubes were placed in a water bath that was cooled with tap water. Irradiation with a 450 watt Hanovia lamp was carried out for 48 hr. Distillation provided 86 g of recovered 1212 which vpc indicated to be unchanged from the starting 1212 and 6.5 g of colorless liquid $b_{7-8} = 40-50^{\circ}\text{C}$. This distillate analyzed on Carbowax 20M as 56% cross adducts and 44% cyclopentadiene dimers. The reaction mixture was then exhaustively hydrogenated in methanol with $\text{PtO}_2 \cdot n\text{H}_2\text{O}$ as catalyst, filtered, and cautiously concentrated.

A comparison of the detailed adduct distributions on Carbowax 20M is instructive: before hydrogenation 5.0% 50, 11.4% 51, 34.6% 52, 16.8% 53, 30.4% 54 + 55, and 1.8% 56 and after hydrogenation 5.3% 57, 46.9% 58, 16.2% 59, 23.1% 61 + 62, and 8.5% 60. The two trans 1,2 adducts of relative areas $\underline{51} + \underline{52} = 11.4 + 34.6 = 46.0\%$ collapse to a common hydrogenated adduct 58 of area 46.9%. This close correspondence between areas before and after hydrogenation indicates

ratio of $(\underline{61} + \underline{62})/\underline{60}$ was 1.54 before starting irradiation and 1.61 after.

Vpc Separation of 1212-Cyclopentadiene Cross Adducts 50-62.

In all but one case it sufficed to use a 10M X $\frac{1}{4}$ " , 20% Carbowax 20M, 40/60P column in conjunction with an F & M Scientific 300 or an Aerograph Autoprep as described on pp. 29-32. The only adduct otherwise requiring special treatment was 56 in the case of the photochemical adduct mixture. Several hundred grams of 1212 not separated into cis and trans isomers but carefully freed of 1122 were photoadded to cyclopentadiene allowing isolation of a yellow oil $b_{7-8} = 40-50^{\circ}\text{C}$. This oil consisting largely of cyclopentadiene dimers was initially pushed through a Carbowax 20M column in near flooding quantities. Adduct 56 was then collected as a bump on the tail of earlier isomers. Two more passes on Carbowax 20M followed by a third pass through a 4M X $\frac{1}{4}$ " , 20% DIDP, 40/60P column sufficed. The 56 isolated in this manner had ^{19}F and ^1H nmr spectra identical to those of 56 produced thermally. This was the only instance in which thermal and photochemical adducts were compared before hydrogenation; rather, all the remaining adducts were isolated only in their hydrogenated form from both thermal and photosensitized reaction mixtures and shown to be identical by ^1H and ^{19}F nmr.

Comparative Chromous Ion Dehalogenation of Hydrogenated 1,4

Cyclopentadiene-1212 Adducts, 60-62. Three separate mixtures each consisting of 25 mg of either 60, 61, or 62 and 0.1 g of Merck zinc dust, 0.1 g of $\text{Cr}_2(\text{SO}_4)_3 \cdot \text{nH}_2\text{O}$, 1 ml of dimethylformamide, and 1 ml of water were sealed under nitrogen in thick wall Pyrex tubes containing a stirring bar. The tubes were heated simultaneously with stirring in the same 110-100°C oil bath for roughly 22 hr.

After cooling in dry ice-acetone, the tubes were opened and their sides washed down with less than 1 ml of pentane. The tubes were warmed until the contents liquified and permitted vigorous shaking. Several ml of water were added after which the tubes were again placed in dry ice-acetone. The pentane layer was decanted into a sample vial once the aqueous layer froze solid. The vial was refrigerated until such time as a vpc analysis could be run with a 10M X 1/8", 20% Carbowax 20M, 60/80W column under conditions previously found to allow isolation of the products by preparative vpc in an analytically pure state from a larger scale reaction. The product distribution is shown in Table I.

Comparative Chromous Ion Dehalogenation of Hydrogenated 1,2

Cyclopentadiene-1212 Adducts, 57-59. Three separate mixtures each consisting of 33 mg of either 57, 58, or 59 and 0.1 g of Merck zinc dust, 0.1 g of $\text{Cr}_2(\text{SO}_4)_3 \cdot \text{nH}_2\text{O}$, 1 ml of dimethylformamide, and 1 ml of water were sealed under nitrogen in thick wall Pyrex tubes

containing a stirring bar. The tubes were heated simultaneously with stirring in the same 95-115°C oil bath for roughly 21 hr.

After cooling in dry ice-acetone, the tubes were opened and their sides washed down with less than 1 ml of pentane. The tubes were warmed until the contents liquified and permitted vigorous shaking. Several milliliters of water were added after which the tubes were again placed in dry ice-acetone. The pentane layer was decanted into a sample vial once the aqueous layer froze solid. The vial was refrigerated until such time as a vpc analysis could be run with a 10M X 1/8", 20% Carbowax 20M, 60/80W column under conditions previously found to allow isolation of the products by vpc in an analytically pure state. The individual product distributions are shown in Table I.

Dehalogenation of Hydrogenated 1,4 Cyclopentadiene-1212 Adducts Using Zinc Alone. Roughly 25 mg of vpc purified adducts 60-62, 0.1 g of Merck zinc dust, 1 ml of water, and 1 ml of dimethylformamide were sealed under nitrogen in a thick wall Pyrex tube with a magnetic stirring bar. The tube was placed in a 110°C oil bath for 3/4 hr and its contents stirred magnetically.

After cooling in dry ice-acetone, the tube was opened and its sides washed down with less than 1 ml of pentane. The tube was warmed until the contents liquified and permitted vigorous shaking. Several milliliters of water were added after which the tube was again placed in dry ice-acetone. The pentane layer was decanted into

a sample vial once the aqueous layer has frozen solid. The vial was refrigerated until such time as a vpc analysis could be run with a 10M X 1/8", 20% Carbowax 20M, 60/80W column: 0.0% 65, 56.2% 66, 27.2% 67, trace (?) 69, 11.6% 61 + 62, and 5.0% 60. Clearly zinc dust is less reactive than the Zn-Cr(II) combination since 61 and 62 would have reacted completely under less vigorous conditions with Zn-Cr(II) (see Table I).

Comments on the Preparative Chromous Ion Dehalogenation of Cyclopentadiene-1212 Hydrogenated Adducts. Preparative scale reactions on 10-20 g of hydrogenated 1212-cyclopentadiene adducts from the thermal and photochemical adduct mixtures were run. The reactions were run in sealed Kjeldahl flasks rather than sealed tubes. Such preparative scale reactions will be described in greater detail for the 1122 and CTFE hydrogenated adducts with cyclopentadiene. Starting with the 1212-cyclopentadiene hydrogenated adducts sufficient quantities of the key dehalogenated compounds 66, 67, 70, and 71 were isolated to allow mass spectral fragmentation patterns, parent peak exact masses, and IR spectra to be taken. The mass spectral fragmentation patterns clearly distinguished 66 and 67 as having 1,4 adduct structure since their base peaks were substituted cyclopentadienes formed by retro Diels-Alder reactions unlike the base peaks of 70 and 71. Eventually these compounds were prepared in larger quantity by the dehalogenation of 1122 and CTFE hydrogenated

adducts. From the dehalogenation of the 1212-cyclopentadiene hydrogenated adducts sufficient quantities of the minor products 65 and 69 were also isolated for IR spectra. Compound 65 was identified by comparison to a commercial sample of norbornene and 69 by comparison to an independently synthesized sample (see below).

Ozonolysis of 2,3-Difluoronorbornene 66 and Other Alkenes 65, 67, 68, and 70-72. Ozone was bubbled through a dry ice-isopropanol cooled solution of 0.94 g of 2,3-difluoronorbornene 66 in ethyl acetate. Excess blue ozone marking completion of the reaction was removed by bubbling through nitrogen. The reaction flask was transferred to a rotary evaporator. The solvent was pulled off as rapidly as possible until its evaporation failed to provide further cooling. The viscous residue was treated immediately with 20 ml of 90% formic acid and 7 ml of 30% hydrogen peroxide. Failure to add the formic acid and hydrogen peroxide as soon as possible has lead to violent decomposition as in the case of 71. The solution was stirred magnetically and the flask fitted with a reflux condenser. Although not in this particular case vigorous heating was frequently observed briefly after adding the formic acid and hydrogen peroxide. In either event a gradual evolution of oxygen began. After several days, when the oxygen evolution had stopped, the solution was refluxed for an hour. The solution was treated with norite, boiled, and gravity filtered. The filtrate was concentrated to a sticky brown solid on a rotary evaporator connected to a high vacuum pump. After agitating briefly with a small quantity of ice water,

Kjeldahl flask. The flask was placed in a 95-100°C oil bath. Stirring was continued until the deep blue color of Cr(II) developed after 22 hr indicating that the reaction was complete. The reaction is slowed considerably if oxygen is not flushed out prior to sealing the Kjeldahl flask. Failure to add HgCl₂ can lead to an eventual violent rupture of the Kjeldahl flask as a result of excessive pressure build up. A protective shield was used at all times.

The flask was cooled in dry ice and opened behind a shield. Pouring the contents on water, extraction with pentane, drying over magnesium sulfate, and distillation gave 8 g (70% assuming pure 67 and 71) of clear liquid $b_{760} = 145-8^{\circ}\text{C}$. Storing in a refrigerator slowed but did not stop the gradual decay of the distillate to solid materials. The products were isolated using a 10M X $\frac{1}{4}$ ", 20% Carbowax 20M, 40/60P column. 98.2% of the total vpc trace area may be accounted for by the following distribution: 0.9% 65, 1.2% 69, 30.5% 71, and 66.2% 67. These components were isolated and related to the same compounds from other reactions by their easily distinguishable IR spectra. This sequence was the major source of 67 and 71 needed for synthesis and further degradation.

Individual Chromous Ion Degradations of Hydrogenated 1122-Cyclopentadiene Adducts 76 and 77. 25 mg of adduct, 0.1 g of Cr₂(SO₄)₃·nH₂O,

1 ml of water, and 1 ml of dimethylformamide were stirred under nitrogen in a sealed tube for a day in a 90-110°C oil bath.

After workup the uncorrected product vpc trace areas on Carbowax 20M were : 95.7% 67, 2.9% 69, and 1.4% unknown from 76 and 97.0% 71 and 3.0% unknown from 77.

Thermal Cycloaddition of Chlorotrifluoroethylene to Cyclopentadiene.

Preparation of 79-82. Four 3/4" I. D. 1" O. D. Pyrex tubes were cooled in a dry ice methanol bath. Roughly 2" of cyclopentadiene were added to the tubes and then 3" of CTFE distilled in. After adding a trace of hydroquinone, the tubes were sealed under nitrogen. Heating for two days at 190°C caused considerable blackening and the formation of intractable solids. The tubes were opened while cooling in liquid nitrogen. Volatiles were allowed to vent into a fume hood as the tubes warmed slowly to room temperature. Distillation gave 33 g of a cloudy colorless liquid $b_{45} = 70-80^{\circ}\text{C}$. Vpc analysis on a 10M X 1/8", 20% 8-methyl-8-nitropimelonitrile column at 150°C indicated four components eluting in their order 79 + 80 (31.0%), 82 (26.7%), and 81 (42.3%).

Hydrogenation of Chlorotrifluoroethylene-Cyclopentadiene Adducts.

Preparation of 83-86. 33 g of cross adducts between cyclopentadiene and CTFE $b_{45} = 70-80^{\circ}\text{C}$ were dissolved in roughly an equal volume of methanol and a trace of $\text{PtO}_2 \cdot n\text{H}_2\text{O}$ added. The mixture was subjected to 45 psi of hydrogen on a Paar hydrogenator. If the catalyst

became poisoned during hydrogenation, the adducts were distilled and run on the hydrogenator repeatedly until full saturation was achieved. Once hydrogenation was complete, norite was added and the reaction mixture gravity filtered. Distillation gave 27 g (80%) of a clear liquid $b_{45} = 80-85^{\circ}\text{C}$. Vpc analysis on Carbowax 20M gave four components eluting in the order 83 (14.5%), 84 (15.9%), and 85 + 86 (69.6%). Comparison to the distribution before hydrogenation followed by minor adjustments to 100% resulted in the distribution cited on p. 50.

Preparative Chromous Ion Dehalogenation of CTFE-Cyclopentadiene Hydrogenated Adducts. Preparation of 66 and 70. 15 g of the adduct mixture 83-86 $b_{45} = 80-85^{\circ}\text{C}$, 30 g of zinc dust, 15 g of $\text{Cr}_2(\text{SO}_4)_3 \cdot \text{nH}_2\text{O}$, 3 g of HgCl_2 , 150 ml of water, 150 ml of dimethylformamide, and a strong stirring bar were sealed under nitrogen in a 500 ml Kjeldahl flask. The flask was placed in a $95-105^{\circ}\text{C}$ oil bath. Stirring at this temperature was continued for 54 hr. The reaction is slowed considerably if oxygen is not flushed out prior to sealing the Kjeldahl flask. Failure to add HgCl_2 can lead to an eventual violent rupture of the flask as a result of excessive pressure build up. A protective shield should be used at all times.

The flask was cooled in dry ice and opened behind a shield. Pouring the contents on water, extraction with pentane, drying over magnesium sulfate, and distillation gave 7 g of clear liquid

the lower frozen aqueous layer. An immediate vpc analysis with a 10M X $\frac{1}{4}$ " , 20% Carbowax 20M, 60/80P column at 150°C indicated 29.1% 121, 0.0% 122, 33.9% 69, 35.5% 65 in addition to some 1.5% of unidentified materials. Once again it would seem that the exo chloro adduct has reacted more rapidly than its corresponding endo chloro isomer. Actual preparative vpc allowed isolation of 0.14 g (13%) of 65 and 0.15 g (11%) of 69, both identical by ^1H nmr and IR to samples from other sources.

Preparation of 68. A mixture of exo- and endo-5,5,6-trichloro-norbornenes was prepared by heating trichloroethylene with cyclopentadiene.^{49h} Hydrogenation of an ethanolic solution of this mixture with $\text{PtO}_2 \cdot n\text{H}_2\text{O}$ as catalyst in a Paar hydrogenator gave 2,2,3-trichloronorbornane $b_9 = 90-100^\circ\text{C}$. 45 g of this crude 2,2,3-trichloronorbornane , 45 g of K & K potassium t-butoxide, and 270-300 ml of dimethylsulfoxide were stirred in a stoppered 500 ml r. b. flask. After 3 hr the reaction mixture was poured onto several liters of water and extracted with three 100 ml portions of methylene chloride and one 100 ml portion of hexane. These extracts were dried over MgSO_4 , filtered, and concentrated to a residue. Distillation gave 14 g (38%) of 68 $b_{760} = 180-85^\circ\text{C}$. For analytical and spectral purposes this material was further purified by passage through a Carbowax 20M vpc column.

Preparation of 72. A mixture of 5,5,6-trichloronorbornenes and 6,6,7-trichlorobicyclo(3.2.0)hept-2-enes was prepared by

photosensitized cycloaddition of cyclopentadiene to trichloroethylene.^{49h}
 80 g of this adduct mixture in 75 ml of methanol was hydrogenated with $\text{PtO}_2 \cdot n\text{H}_2\text{O}$ as catalyst in a Paar hydrogenator. There resulted 67 g (80%) of crude hydrogenated 2,2,3-trichloromorbornanes and 6,6,7-trichlorobicyclo(3.2.0)heptanes $b_9 = 90-100^\circ\text{C}$. 40 g of these hydrogenated adducts, 30 g of K & K potassium t-butoxide, and 200 ml of dimethylsulfoxide were stirred in a stoppered flask for 1 hr. Cooling was applied by an ice bath until the initial heat generation was over. The reaction mixture was poured onto 1200 ml of water and extracted with two 100 ml and two 200 ml portions of pentane. The combined pentane extracts were washed twice with two 500 ml portions of water, dried over MgSO_4 , filtered, and concentrated to a residue. Distillation gave 12 g of yellow liquid $b_{760} = 180-185^\circ\text{C}$. Vpc analysis on 20% Carbowax 20M indicated the following components in the order of their elution time: 35% 72, 51% 68, and 15% unknown. Sufficient 72 was separated by preparative vpc for the degradations and syntheses described in other sections.

Direct Fluorination of 6,7-Dichlorobicyclo(3.2.0)hept-6-ene 72 and of 67, 68, and 71. Preparation of 53, 54, 84, and 86. An all Pyrex cold finger trap was equipped with a fluorine inlet, an outlet to a vacuum pump, a nitrogen inlet, and a mercury manometer protected by Kel-F #3 oil. All ground glass joints were lubricated

with Kel-F #90 grease. The grease was not heated prior to use under a high vacuum as described by Merritt.⁶¹

The cold finger trap was loaded with 1.5 g of freshly bulb-to-bulb distilled 72, 1.5 g of 80 mesh 5A molecular sieves, 100 ml of CFCl_3 , and a teflon stirring bar. The mixture was stirred briefly at room temperature in order to insure full mixing. The cold trap was then lowered into a dry ice-isopropanol bath as stirring was continued. The system was evacuated down to a pressure of several millimeters. Fluorine was bled in until the pressure reading of the mercury manometer climbed some 10 mm. As the fluorine reacted, the pressure returned to its original low level. Fluorine was thus periodically introduced until such time as the pressure failed to recover. The system was flushed with nitrogen and the reaction mixture immediately poured onto $\frac{1}{2}$ g of KOH in 50 ml of water at a rate slow enough to prevent the CFCl_3 from foaming over. The lower CFCl_3 layer was separated, dried over MgSO_4 , and filtered. Evaporation on a rotovac gave 1.7 g of light yellow oil. Vpc analysis on a 10M X $\frac{1}{4}$ " , 20% Carbowax 20M, 40/60P column at 160°C indicated that a multitude of products (perhaps 20 or 30) had been formed. The major vpc peak had the retention time of 59 and accounted for 22% of the total product vpc trace area. Actual preparative isolation gave 0.15 g (8%) of material with ^1H and ^{19}F nmr spectra identical to those of adduct 59. Roughly 9.4% of the total product vpc trace area was

accounted for by a single peak with the retention time of 57. Actual vpc isolation of this peak, however, gave a sample with an ^1H nmr quite unlike that of 57 in that strong absorptions were found around 4.8 and 5.6 δ . The results for all the compounds fluorinated are gathered below,

Compound Fluorinated	Product	Percent Total Vpc Trace Area of Product	Vpc Columns Used for Isolation
<u>67</u>	<u>86</u>	11%	20% Carbowax 20M & 20% DIDP
<u>68</u>	<u>54</u>	35%	20% Carbowax 20M
<u>71</u>	<u>84</u>	24%	20% Carbowax 20M
<u>72</u>	<u>59</u>	22%	20% Carbowax 20M

Iodobenzene Dichloride Chlorination of 6,7-Difluorobicyclo(3.2.0)-hept-6-ene 70 and of 66. Preparation of 57 and 62. 0.37 g of 70, 0.57 g of iodobenzene dichloride, 10 ml of carbon tetrachloride, and a stirring bar were placed in a heavy wall Pyrex tube. The tube was evacuated to less than 5 mm and then sealed. Magnetic stirring was commenced after the reaction mixture was placed in a 60-70°C oil bath. Within about 15 min all solid iodobenzene dichloride had disappeared and the reaction mixture had become colorless. The tube was withdrawn and agitated so as to wash any residual iodobenzene dichloride down off the sides of the tube. Insertion back into the oil

bath then caused the remaining iodobenzene dichloride to disappear rapidly. After stirring for an additional 10 min, the tube was cooled and opened. The contents were washed out with pentane and concentrated by distilling off all volatiles $b_{760} < 79^{\circ}\text{C}$. A vpc of this crude residue was taken on a 10M X $\frac{1}{4}$ ", 20% Carbowax 20M, 40/60P column at 167°C : retention times indicated 13.7% 57, 34.4% 58, 47.7% iodobenzene, and 4.2% unknowns. The nearly equal yields of 57 + 58 = 48.1% and iodobenzene = 47.7% suggested an almost quantitative reaction. Actual preparative vpc gave 65 mg of 57, 121 mg of 58, and iodobenzene identified by their ^1H nmr. In all nmr spectra an extra singlet at 3.6 δ was noted and in fact a material was found to be bleeding from the vpc column that also had a sharp singlet at 3.6 δ . A second pass on a new Carbowax 20M vpc column gave 57 and 58 free of this 3.6 δ singlet. This problem occurred with every new run.

Iodobenzene dichloride chlorination of 66 gave a single product 62.

Preparation of Dichloromethylene-cyclopropane 93. Dichloromethylene-cyclopropane was prepared according to established procedure. A few changes were made in the first step which involved the addition of dichlorocarbene to allene:¹²⁸ 1/ Matheson allene was used without any particular purification, 2/ Fieser's method¹²⁹ was used for sodium

128. H. G. Peer and A. Shors, Rec. Trav. Chim., 86, 161(1967).

129. L. F. Fieser and M. Fieser, Reagents for Organic Synthesis, John Wiley and Sons, Inc., New York, 1967.

trichloroacetate, and 3/ sodium dried Eastman white label 1,2-dimethoxyethane was found to be adequate. In workup the fraction $b_{760} = 90-100^{\circ}\text{C}$ was found to be rich in products and was used in the final purification on a $5\text{M} \times \frac{1}{4}"$, 25% TCEP, 60/80P column at 100°C .

The second step involved the "quantitative" vapor phase rearrangement of 2,2-dichloromethylenecyclopropane to dichloromethylenecyclopropane at 215°C .⁸³ At pressures suitable for preparation of sizable samples of dichloromethylenecyclopropane significant quantities of the dimer 94 were also formed. The conditions finally derived represented a compromise between the generation of a reasonable quantity of dichloromethylenecyclopropane per run and the loss of this dichloromethylenecyclopropane by dimerization: 1.5 g of starting 2,2-dichloromethylenecyclopropane at 205°C for 1 hr in a 3 liter vapor phase reactor. The product thus obtained was passed through a $3\text{M} \times \frac{1}{4}"$, 20% Carbowax 20M, 40/60P column at 105°C . This vpc purified material was bulb-to-bulb distilled before cycloaddition.

Cycloaddition of Dichloromethylenecyclopropane to Butadiene.

Preparation of 95. Roughly 20 g of butadiene and 1 ml of dichloromethylenecyclopropane were heated in a sealed Pyrex tube under nitrogen for 60 hr at 80°C . The tube was opened and its contents poured into a 100 ml r. b. flask. After a single degassing the yellow residue was bulb-to-bulb distilled producing 1.9 g of oil and leaving behind a glassy yellow residue. This oil consisted largely of 4-vinylcyclohexene

and adduct 95. Preparative vpc with a 1M X $\frac{1}{4}$ " , 20% Carbowax 20M, 30/60W AW DMCS column at 100°C gave 0.84 g (70%) of 95 with a 15 min retention time. For such vpc purified 95,

Anal. Calc. for $C_8H_{10}Cl_2$: C, 54.26; H, 5.69

Found: C, 54.00; H, 5.58

Preparation of 1,1-bis(Trifluoromethyl)-2,2-dichloroethylene 100.

A 24/40 joint and a side arm were attached to a heavy wall Pyrex tube above its constricted neck. The tube was loaded with 5 g of triphenylphosphine and 25 ml of bromotrichloromethane taking care to avoid any contact with the constricted neck. Nitrogen was blown in through the side arm as a dry ice condenser protected by a $CaCl_2$ tube was connected to the 24/40 joint at the top of the tube. The dry ice condenser was filled with dry ice and methanol as the tube was lowered into a dry ice-methanol bath. The nitrogen flow was stopped briefly while hexafluoroacetone was run in the side arm of the tube. The hexafluoroacetone liquified at the dry ice condenser and eventually collected at the bottom of the tube. Once roughly 5 ml had collected, the hexafluoroacetone flow was stopped and the nitrogen flow resumed. The neck of the tube was sealed with a vigorous stream of nitrogen continuing all the while through the inlet tube above the constricted neck. After heating for 6 hr at 70°C, the tube was cooled in dry ice-methanol and then opened. While still cool the heavy, heterogeneous green product was decanted into a 50 ml r. b. flask. Distillation

with heavy foaming through a micro Widmer column produced 1.5 ml of colorless liquid $b_{760} = 73-90^{\circ}\text{C}$. Passage on a 10M X $\frac{1}{4}$ " , 20% Carbowax 20M, 30/60W AW DMCS column at 65°C gave 0.8 g (30% based on triphenylphosphine) of pure 100 with a 5 min retention time. Other major vpc peaks following 100 were CCl_4 (23 min) and CBrCl_3 (55 min). On account of high volatility 100 was stored in the refrigerator. All operations were performed in a fume hood.

Attempted Dimerization of 1,1-bis(Trifluoromethyl)-2,2-dichloroethylene 100. 100 μl of 100 were heated under nitrogen in a sealed Pyrex tube for 23 hr at 250°C . The 80 μl of recovered clear liquid had the same IR, vpc retention time, and mass spectrum as the original sample of 100.

Attempted Cycloaddition of 1,1-bis(Trifluoromethyl)-2,2-dichloroethylene 100 to Butadiene.

A. 25 μl of 100 and 0.4 g of butadiene were heated in a sealed tube under nitrogen for 24 hr at 100°C and for 5 hr at 180°C . On opening and evaporating to a residue both reactions showed a single major product with the vpc retention time of 4-vinylcyclohexene.

B. 50 μl of 100 and 0.4 g of butadiene were heated in a sealed tube under nitrogen for 7 hr at 250°C . The tube was cooled before and after opening in order to insure minimal loss of volatile materials. Vpc analysis on Carbowax 20M and TCEP at different temperatures indicated the following product distribution in the order of increasing

retention time.

Product	Area Percent
Butadiene	4.8%
<u>100</u>	12.5%
4-vinylcyclohexene	75.8%
unknown	0.3%
(Butadiene) _n	6.5%
unknown	0.1%

The most volatile material was assumed to be butadiene while the 12.5% product had the retention time of 100 and was assigned accordingly. Little effort was expended in their identification inasmuch as their retention times were much too short for consideration as an adduct. The 75.8% product was collected by preparative vpc and identified as 4-vinylcyclohexene by nmr comparison to an authentic sample and a consistent mass spectrum. Preparative vpc of the 6.5% product followed by mass spectral analysis showed peaks at: mass (intensity) -- 108(17), 93(29), 80(78), 79(72), 77(25), 67(168), 66(34), 54(201), 53(26), 51(20), and 39(84) suggesting a butadiene dimer or trimer structure. Isolation of the 0.3 and 0.1% peaks was impractical.

Thermal Cycloaddition of 1122 to trans-Cyclooctene. Preparation

of 101 and 102. Two tubes each containing 4 g of 99% pure trans-cyclooctene¹³⁰ and 16 g of 1122 were sealed under nitrogen and placed in a preheated oven at 120-130°C for 3 hr. The tubes were opened and gave 26 g of recovered 1122. The remaining material was subjected to a vacuum of 10 mm while heating gently. Roughly 0.5 g of material was collected in a flask cooled in dry ice-acetone. This low boiling fraction was subjected to preparative vpc with a 4M X $\frac{1}{4}$ " , 25% TCEP on 60/80P AW column at 125°C. The major components in an 88:12 ratio gave the IR spectra of cis-cyclooctene and trans-cyclooctene respectively. Continuing the distillation gave 6.1 g (69%) of colorless oil $b_{11} = 106-8^{\circ}\text{C}$. Vpc analysis on Carbowax 20M indicated that this fraction was 99% 102 and 1% 101. Pushing the whole through a preparative Carbowax 20M column resulted in 5.6 g (63%) of 102 and 35 mg (0.5%) of 101. This sample of 102 gave the mass spectrum, ^1H nmr, ^{19}F nmr and IR spectrum hereafter considered standard for 102. The sample of 101 on a second pass through Carbowax 20M gave roughly 20 mg of material with ^1H nmr and IR identical to those for a genuine sample of 101. In order to put these results in their proper perspective a number of controls were run.

Roughly 50 μl of cis-cyclooctene were heated under nitrogen at 120-130°C for 28 hr with 0.3-0.5 g of 1122. At the end of this period

130. a/ A. C. Cope, R. A. Pile, and C. F. Spencer, J. Am. Chem. Soc., 75, 3212(1953). b/ J. L. Coke and M. C. Mourning, J. Am. Chem. Soc., 90, 5561(1968).

no cis fused adduct 101 could be detected. Thus, the 101 detected above truly arose in the reaction of trans-cyclooctene with 1122 rather than from a competing cycloaddition of cis-cyclooctene to 1122.

About 25 μ l of pure 102 in 0.2-0.4 g of 1122 were heated under nitrogen for 11 hr at 185°C. No cis fused adduct could be detected in the reaction mixture on recovery. Approximately 30 μ l of pure cis fused adduct 101 in 0.4-0.6 g of 1122 were heated under nitrogen for 25 hr at 185°C. No trans fused adduct 102 could be detected in the reaction mixture on recovery. The distribution of the adducts 101 and 102 on cycloaddition of 1122 to trans-cyclooctene thus did not reflect any interconversion under the reaction conditions.

In a sealed Pyrex tube 30 μ l of pure cis fused adduct 101 were heated under nitrogen in 0.4-0.6 g of 1122 for 25 hr at 185°C. No cis-cyclooctene could be detected in the recovered reaction mixture. The heating of a 0.2-0.3 g sample of pure trans fused adduct 102 in 0.2-0.3 g of 1122 under nitrogen for 3 hr at 155°C also failed to produce any cis-cyclooctene. The cis-cyclooctene in the product mixture from the cycloaddition of 1122 to trans-cyclooctene thus could not be accounted for by retro addition.

Roughly 50 μ l of 99% pure trans-cyclooctene and 0.3-0.5 g of 1122 were heated under nitrogen at 120-30°C for 3 hr. The recovered cyclooctene was likewise 99% trans. On heating 50 μ l of trans-cyclooctene in 0.5 g of pentane for 3 hr at 125°C, there resulted 3% isomerization to cis-cyclooctene whereas use of acetonitrile in the place of pentane

resulted in 7% isomerization. Concerted cycloaddition of trans-cyclooctene to butadiene resulted in little if any isomerization of trans-cyclooctene to cis-cyclooctene (see below). Most likely then not all of the cis-cyclooctene observed in the cycloaddition of 1122 to trans-cyclooctene resulted from the thermal isomerization of the trans-cyclooctene.

About 50 μ l of 99% trans-cyclooctene and 0.3-0.5 g of 1122 were heated under nitrogen at 120-30°C for three hours. The tube was opened and its contents analyzed by vpc without any workup: 101 (1), 102 (99), and cis-cyclooctene (9). With correction for the 1% cis impurity in the starting trans-cyclooctene, the relative quantities were readjusted to 101 (1), 102 (99), and cis-cyclooctene (8). This correction for the cis-cyclooctene in the starting trans-cyclooctene assumed that the area of cyclooctene and adduct peaks were directly proportional to their mole percents. This assumption was checked by preparing a solution of 35 mg of cis-cyclooctene (16.7 mole percent) in 386 mg of 102 (83.3 mole percent). Injection of this standard solution gave 83.8 area percent for 102 and 16.2 area percent for cis-cyclooctene on a Carbowax 20M column in an F & M Scientific Model 700 thermal conductivity vpc.

For the distribution of cyclooctene between cis and trans isomers a 4M X $\frac{1}{4}$ " , 25% TCEP, 60/80P AW column was used.^{128b} For the distribution of cyclooctene relative to adducts or for the distribution

of adducts relative to one another a 3M X $\frac{1}{4}$ " , 20% Carbowax 20M, 30/60W AW DMCS column was used.

Thermal Cycloaddition of cis-Cyclooctene to 1122. Preparation of 101. In a sealed tube 10 g of cis-cyclooctene and 37 g of 1122 were heated under nitrogen for 16 hr at 185°C. Vpc analysis of the resulting yellow solution suggested that the major product was cis fused adduct 101 with a peak area some 3% as great as that of unreacted cis-cyclooctene. Distillation gave a large fraction $b_{60} = 60-70^\circ\text{C}$ and 1.7 g of residue. The $b_{60} = 60-70^\circ\text{C}$ fraction afforded a pure IR sample of cis-cyclooctene after a single pass on a 3M X $\frac{1}{4}$ " , 20% Carbowax 20M, 30/60W AW DMCS column at 160°C. Passage of the 1.7 g of residue through the same Carbowax 20M column produced 0.3 g (1.4%) of clear oil with the correct IR, ^1H , and ^{19}F spectra for the cis fused adduct 101.

A study of the initial vpc trace revealed a minor product of 3-4% the area of 101 and with the retention time of 102. Preparative vpc first on Carbowax 20M and then on a 4M X $\frac{1}{4}$ " , 25% TCEP column produced several milligrams of material. The IR spectrum obtained was weak but remarkably like that of 102. The mass spectrum of this material showed a number of extraneous peaks in addition to the parent peaks expected for a genuine sample of 102.

Independent Synthesis of cis Fused Adduct 101. A solution

of 6.0 g of cis-9,9-dichloro-10,10-difluorobicyclo(6.2.0)deca-2,4,6-triene 103⁹⁸ in 60 ml of methanol was hydrogenated at atmospheric pressure with $\text{PtO}_2 \cdot n\text{H}_2\text{O}$ as catalyst. When virtually no hydrogen was absorbed during the first day, the reaction mixture was treated with norite and filtered. New $\text{PtO}_2 \cdot n\text{H}_2\text{O}$ was added permitting exhaustive hydrogenation to now proceed readily. Methanol was removed by distillation at atmospheric pressure. Further distillation gave 0.2 g of colorless oil $b_{11} = 108-13^\circ\text{C}$ and 4.8 g of colorless oil $b_{11} = 113-6^\circ\text{C}$. The $b_{11} = 113-6^\circ\text{C}$ fraction was at least 70% a single product which was collected off Carbowax 20M. The mass, IR, ^1H , and ^{19}F spectra of this product were taken as standard for 101.

Chromous Ion Dehalogenation of Adduct 101. Preparation of 104.

3.0 g of cis fused adduct 101, 6 g of zinc dust, 3 g of $\text{Cr}_2(\text{SO}_4)_3 \cdot n\text{H}_2\text{O}$, 0.6 g of HgCl_2 , 30 ml of dimethylformamide, 30 ml of water, and a stirring bar were sealed under nitrogen in a 300 ml Kjeldahl flask. The lower portion of the flask was suspended for a day in a $95-100^\circ\text{C}$ oil bath while its contents were stirred vigorously. When the flask was opened, 100 ml of water were added. Then 15 ml of pentane were added and shaken vigorously with the contents of the flask. The flask was seated on dry ice freezing the aqueous layer and allowing the pentane layer to be decanted. This pentane extract was combined with two later ones and concentrated by distillation at atmospheric

pressure to an oil. Preparative separation on Carbowax 20M allowed 1.6 g (69%) of the major product 104 to be isolated.

Chromous Ion Dehalogenation of 102. Preparation of 106. 4 g of thermal trans-cyclooctene adducts with 1122 (99% 102, 1% 101), 8 g of zinc dust, 4 g of $\text{Cr}_2(\text{SO}_4)_3 \cdot n\text{H}_2\text{O}$, 0.8 g of HgCl_2 , 40 ml of water, 40 ml of dimethylformamide, and a stirring bar were sealed under nitrogen in a Kjeldahl flask. The flask was cooled and opened. The contents of the flask were vigorously shaken after the addition of 15 ml of pentane and 100 ml of water. The reaction mixture was frozen by placing the flask on dry ice. The pentane layer was decanted and combined with a later 10 ml pentane extract of the reaction mixture. The combined pentane extract was dried, filtered, and concentrated by distillation at atmospheric pressure. Distillation of the residue gave 2.0 g (62%) of clear colorless 106 $b_{25} = 110-114^\circ\text{C}$. Final purification was effected on a 3M X $\frac{1}{4}$ ", 20% Carbowax 20M, 30/60W AW DMCS column at 165°C .

Ozonolysis of 104 and 106. Preparation of 105 and 107. 1 g of 104 was dissolved in 20 ml of ethyl acetate. Ozone was bubbled through the solution in a dry ice-acetone bath until the reaction mixture turned blue. The reaction mixture was washed into a 125 ml r. b. flask. Most ethyl acetate was removed on a rotary evaporator at high vacuum so as to keep the flask below room temperature. To the resulting heavy oil 20 ml of 90% formic acid and 7 ml of 30% hydrogen peroxide were added. The flask was fitted with a reflux

condenser and magnetic stirrer. After roughly 20 hr the reaction mixture was refluxed briskly for 1 hr. Norite was added to the solution which was gravity filtered hot. Evaporation of the filtrate on a rotary evaporator gave 0.8 g of solid which was washed onto a vacuum filter with ice water. Once dry the crystals were dissolved in refluxing methylcyclohexane-ether. The resulting solution was treated with norite and gravity filtered. After concentration and cooling, the filtrate gave 0.26 g of white solid (23%). This material had the IR spectrum of a carboxylic acid, mp = 159-61°C (rptd. mp = 161-2°C),⁹⁹ and hence was assigned the structure 105.

Similar ozonolysis of 106 afforded 36% of 107 mp = 144-6°C (rptd. mp = 145-7°C).⁹⁹

Thermal Cycloaddition of 1212 to trans-Cyclooctene. Roughly 42 g of 1212 and 15 g of 60% trans-, 40% cis-cyclooctene were heated under nitrogen in a sealed tube for 14 hr at 170°C. Distillation at atmospheric pressure gave 33 g of recovered 1212. Further distillation gave roughly 10 ml of impure cis-cyclooctene $b_{50} = 60-70^{\circ}\text{C}$, 0.7 g $b_{10} < 40^{\circ}\text{C}$, 0.3 g $b_{10} = 110-112^{\circ}\text{C}$, and 10.1 g (51%) of adducts $b_{10} = 112-115^{\circ}\text{C}$. No evidence could be found for the cycloaddition of 1212 to cis-cyclooctene under these conditions.

The separation of the individual adducts by vpc was rather difficult.

Separation was accomplished with various combinations of passes on a 4M X $\frac{1}{4}$ ", 25% TCEP, 60/80P column (referred to as column I) and on a 3M X $\frac{1}{4}$ ", 20% Carbowax 20M, 30/60W AW DMCS column (referred to as column II). It was found empirically that adducts collected off TCEP were considerably cleaner if they were first mixed with an equal volume of pentane before injection.

Adduct 112: 20 μ l injections of the pentane solution of adducts $b_{10} = 112-5^{\circ}\text{C}$ were passed on column I at 165°C . The material collected was remixed with pentane and put through column I a second time at 142°C in 30 μ l injections.

Adduct 113: 20 μ l injections of the pentane solution of adducts were passed on column I at 165°C . The material collected was remixed with pentane and put through column I at 142°C in 15 μ l injections. This material was in turn put through column II at 150°C in 15 μ l injections.

Adduct 114: When the $b_{10} = 112-5^{\circ}\text{C}$ fraction was cooled, crystals formed that were separable by vacuum filtration. Three recrystallizations from methanol gave white crystals rich in 114, mp = $69-71^{\circ}\text{C}$. The remaining impurities were removed by a single pass through column II at 150°C .

Adduct 115: The original filtrate from which the adduct 114 had been first crystallized was now somewhat richer in 115 than the original mixture and was more suitable for vpc separation since

the peak immediately preceding 115 on the vpc was the one partially removed by crystallization. This filtrate was mixed with pentane and put through column I at 150°C in 100 µl injections. After a second pass on column I the IR and nmr spectra of 115 were taken without a formal vpc check on its purity. Luckily its fluorine nmr revealed no extraneous compounds. The nmr sample was then given a single pass on column II with the material collected being used to determine the mass spectrum of 115. This pass on the vpc vindicated the previous assumption that 115 had indeed been separated entirely from the other adducts.

Thermal Stability of 1212 Adducts with trans-Cyclooctene.

A. Stability of 113: 10 µl of purified adduct 113 was heated in 0.2-0.4 g of 1212 for 16 hr at 172°C. At the end of this period the tube was opened and its contents allowed to evaporate to a heavy oil. This residue was chromatographed on a 10M X 1/8", 20% Carbowax 20M, 60/80W column at 165°C. Only a single material with the retention time of starting 113 was apparent. No rearranged or additional materials were detected.

B. Stability of a 112-115 mixture: An adduct mixture (18.2% 112, 47.4% 113, 32.4% 114, and 2.0% 115) was heated at 172°C for 18 hr in roughly 0.4 g of 1212. On recovery the mixture analyzed as 17.9% 112, 45.4% 113, 34.0% 114, and 2.7% 115.

Cycloaddition of trans- and cis-1212 to trans-Cyclooctene.

Only the cycloaddition of trans-1212 to trans-cyclooctene will be described in any detail since the other runs contributing to Table V on page 98 were performed simultaneously in an identical manner. Roughly 30 μ l of 99% pure trans-cyclooctene and 1.2 g of 99.3% pure trans-1212 were separately bulb-to-bulb distilled into a thick wall Pyrex tube. The tube was sealed under high vacuum while cooling its contents in liquid nitrogen. After heating for 14 hr. at $172 \pm 5^\circ\text{C}$, the tube was opened and its contents poured into a 14/20 flask which was then refrigerated. Analysis on a 1.25M X 1/8", 5% DMSO, 80/100 alumina column at 0°C indicated that the recovered 1212 was 99.0% trans and 1.0% cis. The 1212 was removed by bulb-to-bulb distillation giving a residue which was analyzed on a 10M X 1/8", 20% Carbowax 20M, 60/80W column at 165°C : 27.2% 112, 20.2% 113, 49.2% 114, and 3.4% 115. The results starting with 95.4% cis-1212 and 51.3% cis-1212 are shown in Table V on page 98 together with those for the 99.3% trans-1212 just described.

Unfortunately it was necessary to use 99% pure trans-1212 and 95% cis-1212 in the studies above. If the cis- and trans-1212 do not cycloadd trans-cyclooctene at fairly comparable rates, it is quite possible that the more rapid reaction of the 1212 isomer present in lesser quantity could lead to a distorted and misleading product distribution. Consider the following idealized runs,

is little more than the uncertainty of $\pm 1\%$ in its vpc determination. Apparently we need not worry about a great difference in reactivity between cis- and trans-1212 in their cycloadditions to trans-cyclooctene.

Preparative Chromous Ion Dehalogenation of the 1212 Adduct Mixture with trans-Cyclooctene. Preparation of 116. Roughly 10 g of adduct mixture (18% 112, 47% 113, 34% 114, 1% 115), 20 g of zinc dust, 10 g of $\text{Cr}_2(\text{SO}_4)_3 \cdot n\text{H}_2\text{O}$, 2 g of HgCl_2 , 100 ml of water, and 100 ml of dimethylformamide, were stirred magnetically under nitrogen in a sealed 500 ml Kjeldahl flask. After 40 hr in a 95-100°C oil bath, the flask was cooled with dry ice and placed behind a safety shield. Touching a scratch on the flask with a hot glass rod caused it to blow open with considerable force and a small blue flame. The contents were shaken with 25 ml of pentane and 200 ml of water. After cooling with dry ice in order to refreeze the aqueous layer, the pentane was decanted. Two more such pentane extracts were combined with the first. Distillation at atmospheric pressure removed the pentane. Rapid distillation of the residue gave the following fractions,

#1 b_{45} = 98-110°C, 3.25 g

#2 b_{45} = 110-35°C, 0.7 g

#3 b_{45} = 135-52°C, 1.3 g

Fraction #1 was at least 95% 116, fraction #2 at least 85% 116, and fraction #3 roughly 74% starting material with the largest proportion of 106 of any fraction.

Preparative vpc of fraction #3 on a 3M X $\frac{1}{4}$ " , 20% Carbowax 20M, 30/60W AW DMCS column allowed separation of impure 106. A second pass on a 4M X $\frac{1}{4}$ " , 20% DIDP, 60/80P column at 155°C gave pure 106 except for some stripping on the part of the column packing. A third pass on Carbowax 20M gave pure 106 identified by IR and mass spectral comparison to a genuine sample.

On slower, more careful distillation fraction #1 was redistilled $b_{32} = 89-92^{\circ}\text{C}$. For degradative and nmr spectral purposes a middle cut $b_{32} = 90-91^{\circ}\text{C}$ was employed. This middle cut was quite pure except for a small 1-2% material that showed up on the tail of 116 when subjected to vpc analysis on a 10M X $\frac{1}{8}$ " , 20% Carbowax 20M, 60/80W column at 140°C. Similarly there was a small blip in the baseline of the ^{19}F nmr of 116. It was not unreasonable to assume this small impurity corresponded to the cis ring fused isomer of 116 that may arise from dehalogenation of the 1-2% of 115 in the starting adduct mixture. Preparative vpc was employed for IR and mass spectral samples of 116 where purity was more critical and smaller samples were practical. The first part of 2-3 μl injections of the fraction $b_{32} = 90-91^{\circ}\text{C}$ coming through a 10M X $\frac{1}{4}$ " , 20% Carbowax 20M, 30/60W AW DMCS column at 155°C gave 116 free of this minor

impurity.

Running a somewhat smaller scale dehalogenation on the same adduct mixture for 60 hr caused the reaction to go to completion. The product distribution before distillation and separation into fractions was 1% 106 and 97-99% 116 depending upon whether 0-2% of material was hidden under the tail end of the 116 peak. On isolation 116 proved identical to that isolated above.

Ozonolysis of 116. Perhaps the ozonolysis of 116 was the most troublesome of the series. Ozone was bubbled through a dry ice-isopropanol cooled solution of 0.9 g of freshly bulb-to-bulb distilled 116 in 10 ml of ethyl acetate until the solution turned blue. Excess ozone was blown out with nitrogen. The ethyl acetate solution was transferred to a rotary evaporator operating under high vacuum. Once the rate of evaporation of ethyl acetate slowed sufficiently to allow the residue to warm above 0°C, the flask containing the residue was transferred to a dry ice-isopropanol bath. To the chilled residue 20 ml of 88% formic acid and 7 ml of 30% hydrogen peroxide were added. The solution was stirred magnetically at r. t. for 3½ days after which time the gradual rate of oxygen evolution perceptibly slowed. The reaction mixture was refluxed for 1 hr after which it was treated with norite and filtered. Concentration on a rotary evaporator produced a heavy orange oil that failed to crystallize from methylocyclohexane-ether. Extended evaporation on a rotary evaporator of this methylocyclohexane-

ether solution produced an oil that eventually changed to a sticky solid. The solid was washed onto a vacuum filter with water. Repeated washings with ice water followed by sucking dry overnight gave 0.48 g of sweet-smelling, greenish-yellow crystals. The crystals were dissolved in refluxing ether, treated with norite, and filtered. Addition of methylcyclohexane and cooling produced 0.16 g of white crystals, mp = 146-8°C (rptd. 145-7°C⁹⁹), corresponding to acid 107.

Comparison of Biradical Reactivity of 1122 and Vinylidene Chloride towards trans-Cyclooctene. In vinylidene chloride the fluorines of 1122 have been replaced by hydrogen. From earlier work it will be recalled that 1122 cycloadded trans-cyclooctene in 69% yield on heating for 3 hr at 125°C.

Roughly 100 μ l of a mixture analyzing as 20.3% cis-cyclooctene, 26.7% trans-cyclooctene, and 53.0% p-xylene were syringed into a Pyrex tube containing 1.0-1.2 g of freshly distilled vinylidene chloride. After sealing under nitrogen the tube was heated at 125°C for 3 hr and then opened. On a 4M X $\frac{1}{4}$ ", 25% TCEP, 60/80P column at 110°C the product mixture analyzed for (excluding vinylidene chloride) 20.2% cis-cyclooctene, 28.9% trans-cyclooctene, and 51.1% p-xylene. The product mixture was then put through a 3M X $\frac{1}{4}$ ", 20% Carbowax 20M, 30/60 W AW DMCS column at 185°C and no adduct peaks were observed out to retention times six times as long as those for known trans-cyclooctene cycloadducts with 1122. Clearly vinylidene chloride does not possess a biradical reactivity approximating that of 1122.

Comparison of Biradical Reactivity of 1,2-Dichloroethylene and 1,2-bis(Trifluoromethyl)-1,2-dichloroethylene to that of 1212. It will be recalled that 1212 cycloadded trans-cyclooctene in 51% yield on heating for 14 hr at 170°C.

A. 1,2-Dichloroethylene: In 1,2-dichloroethylene the fluorines of 1212 have been replaced by hydrogen. Roughly 100 μ l of a mixture analyzing as 20.3% cis-cyclooctene, 26.7% trans-cyclooctene, and 53.0% p-xylene were syringed into a Pyrex tube containing 0.5-0.6 g of 1,2-dichloroethylene (cis- and trans-1,2-dichloroethylene $b_{760} = 50-8^\circ\text{C}$). After sealing under nitrogen, the tube was heated at 170°C for 14 hr. On a 4M X $\frac{1}{4}$ " , 25% TCEP, 60/80P column at 110°C the product mixture analyzed for 22.1% cis-cyclooctene, 24.0% trans-cyclooctene, and 53.9% p-xylene. The product mixture was next put through a 3M X $\frac{1}{4}$ " , 20% Carbowax 20M, 30/60W AW DMCS column at 185°C and no likely adduct peaks were observed out to retention times six times as long as those for known trans-cyclooctene adducts with 1212.

B. 1,2-bis(Trifluoromethyl)-1,2-dichloroethylene: A commercial mixture of cis- and trans-1,2-bis(trifluoromethyl)-1,2-dichloroethylene was obtained from Peninsular Chemresearch of Gainesville, Florida. In the ^{19}F nmr spectrum singlets of roughly equal intensity were observed at 60 ϕ and 64 ϕ indicating a roughly 50:50 mixture of cis and trans isomers.

In 1,2-bis(trifluoromethyl)-1,2-dichloroethylene the fluorines of 1212 have been replaced by trifluoromethyl groups. Roughly 100 μ l of a mixture analyzing as 20.3% cis-cyclooctene, 26.7% trans-cyclooctene, and 53.0% p-xylene were syringed into a Pyrex tube containing 0.5-0.6 g of a cis-trans-1,2-bis(trifluoromethyl)-1,2-dichloroethylene mixture. After sealing under nitrogen, the tube was heated at 170°C for 14 hr and then opened. On a 4M X $\frac{1}{4}$ " , 25% TCEP, 60/80P column at 110°C the product mixture analyzed for 33.7% cis-cyclooctene, 9.5% trans-cyclooctene, and 56.8% p-xylene. On a 3M X $\frac{1}{4}$ " , 20% Carbowax 20M, 30/60W AW DMCS column at 185°C no likely adduct peaks could be found out to retention times six times as long as for those of known trans-cyclooctene cycloadducts with 1212.

Apparently neither 1,2-dichloroethylene nor 1,2-bis(trifluoromethyl)-1,2-dichloroethylene retain the biradical reactivity originally found in 1212.

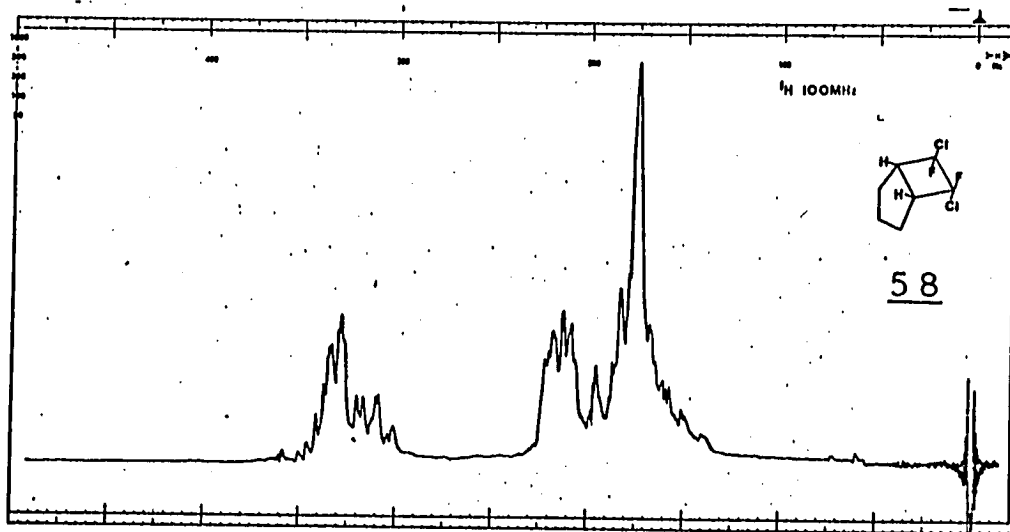
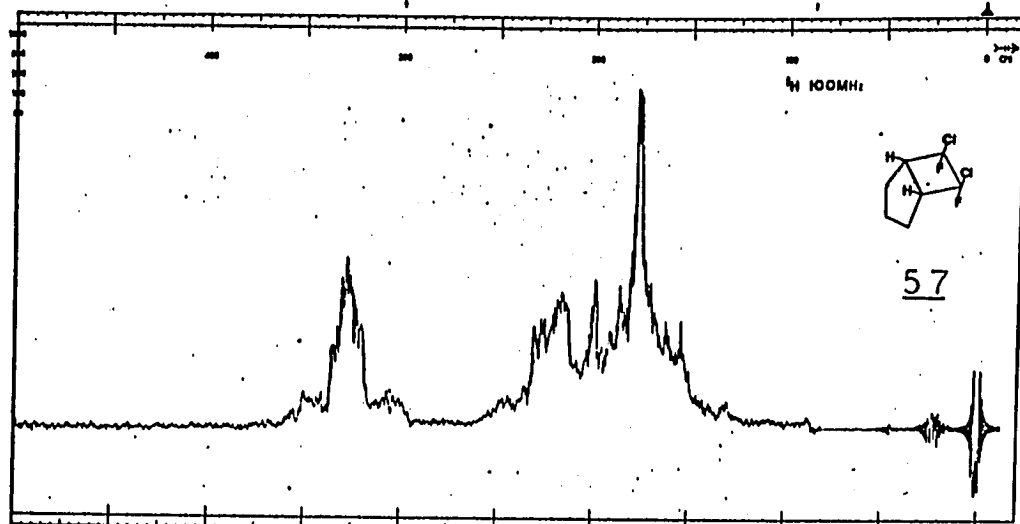
Cycloaddition of trans-Cyclooctene to Butadiene. Roughly 20 g of butadiene, 5 g of 60% trans-, 40% cis-cyclooctene, and a trace of hydroquinone were heated for 2 hr at 125°C in a sealed tube under nitrogen. Fractional distillation of the product was carried out in a large flask on account of a tendency to foam strongly. There was obtained 2.7 ml b_{43} = 55-61°C, 0.5 ml b_{43} = 61-142°C, and 3.4 ml b_{43} = 142-3°C. For 1 H and mass spectral purposes the b_{43} = 142-3°C fraction was distilled a second time giving 2 g (45%) of bicyclo(6.4.0)dodec-10-ene b_{10} = 102-3°C. This material gave a single vpc peak on a 3M X $\frac{1}{4}$ " ,

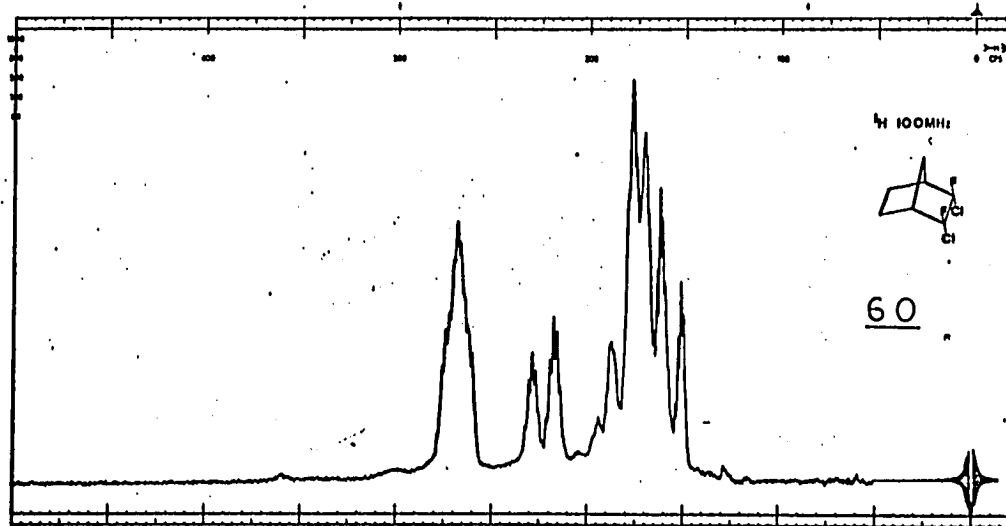
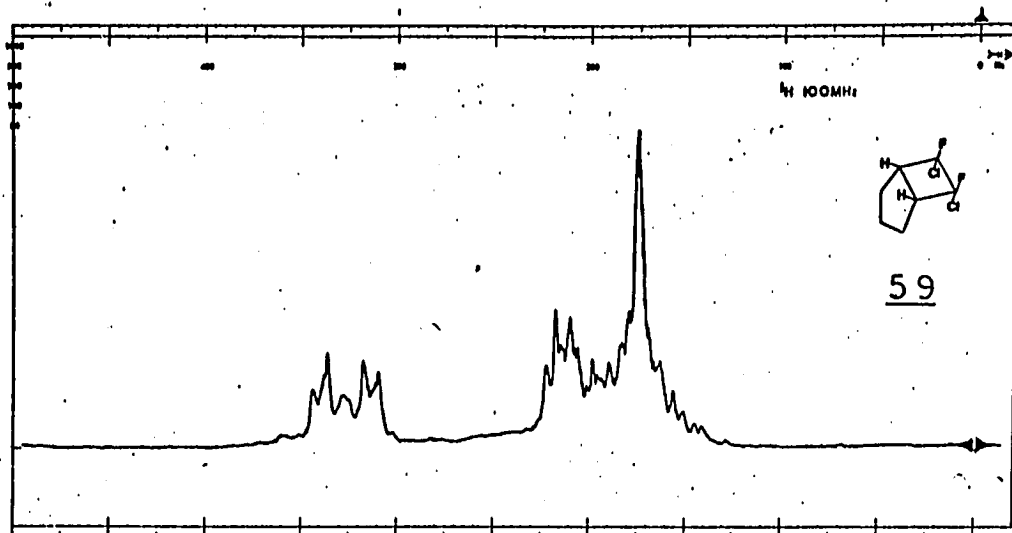
20% Carbowax 20M, 30/60W AW DMCS column at 162°C with a 29 min retention time.

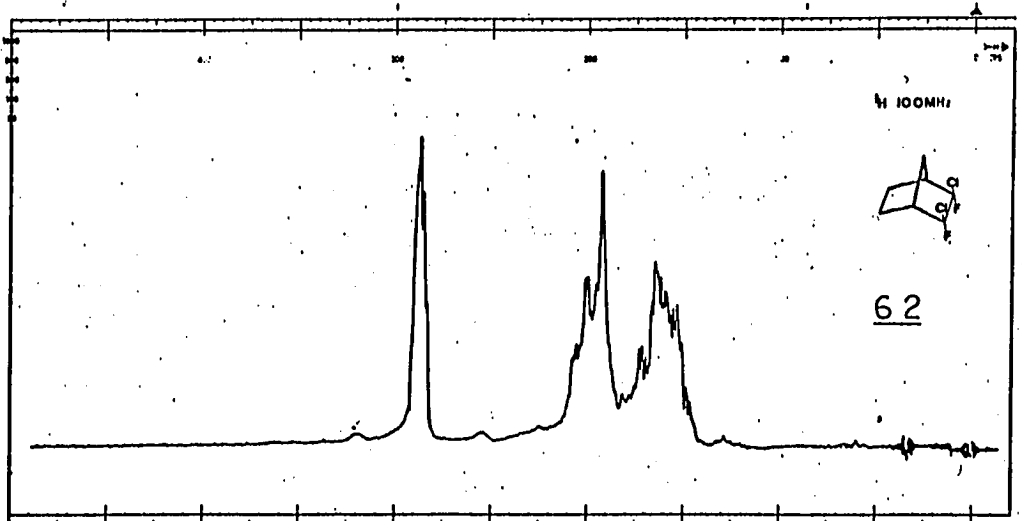
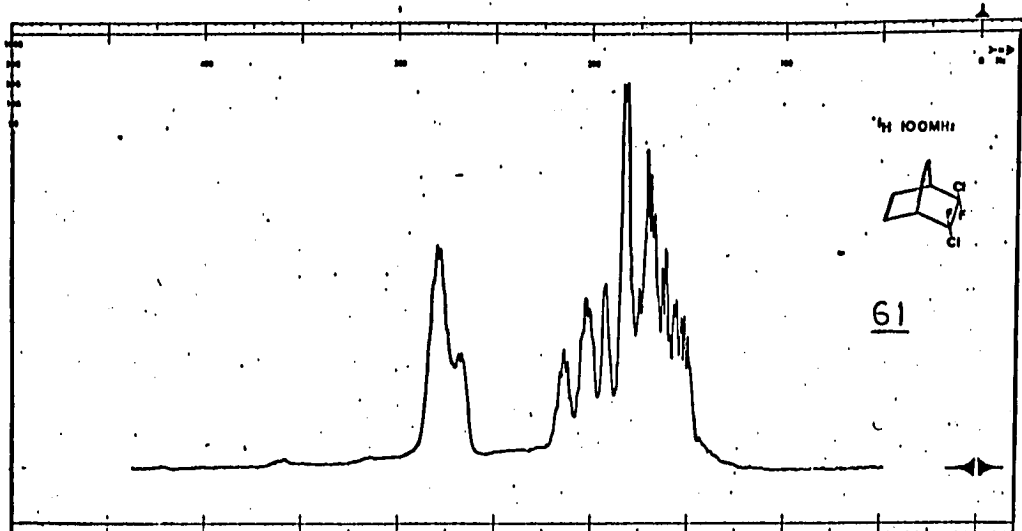
A small scale control reaction was run in order to determine the extent of isomerization of trans- to cis-cyclooctene under the reaction conditions. Roughly 50 μ l of 98.6% pure trans-cyclooctene and 0.25 g of butadiene were heated under nitrogen for 2 hr at 125°C. Vpc analysis at the end of this period gave the following uncorrected vpc trace areas on TCEP: 4-vinylcyclohexene (8.3), cis-cyclooctene (1.0), trans-cyclooctene (1.1), and adduct (97.9). Vpc areas were left uncorrected on the basis of a sample of 114.8 mg of adduct (76.9 mole percent) mixed with 23.2 mg of cis-cyclooctene (23.1 mole percent) which showed relative vpc trace areas of 78.6 for adduct and 21.4 for cis-cyclooctene.

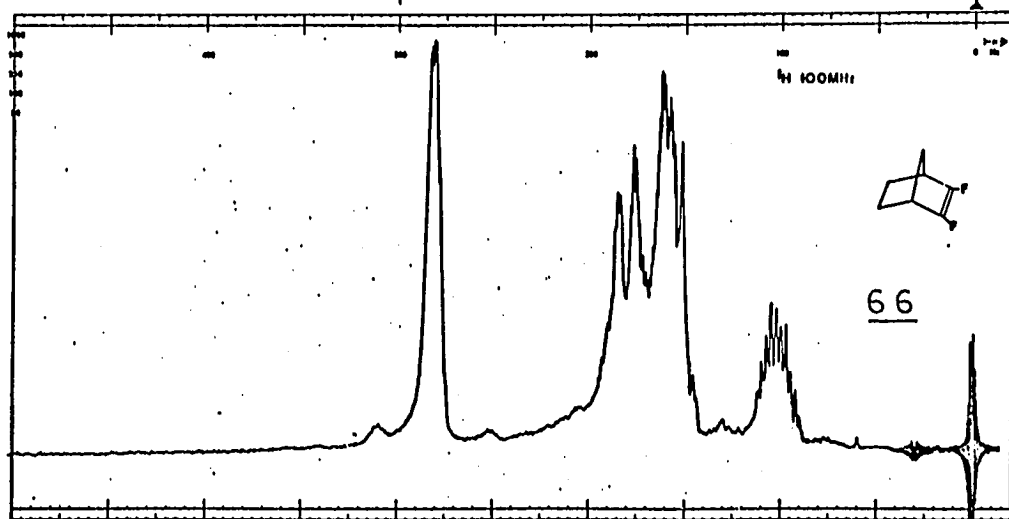
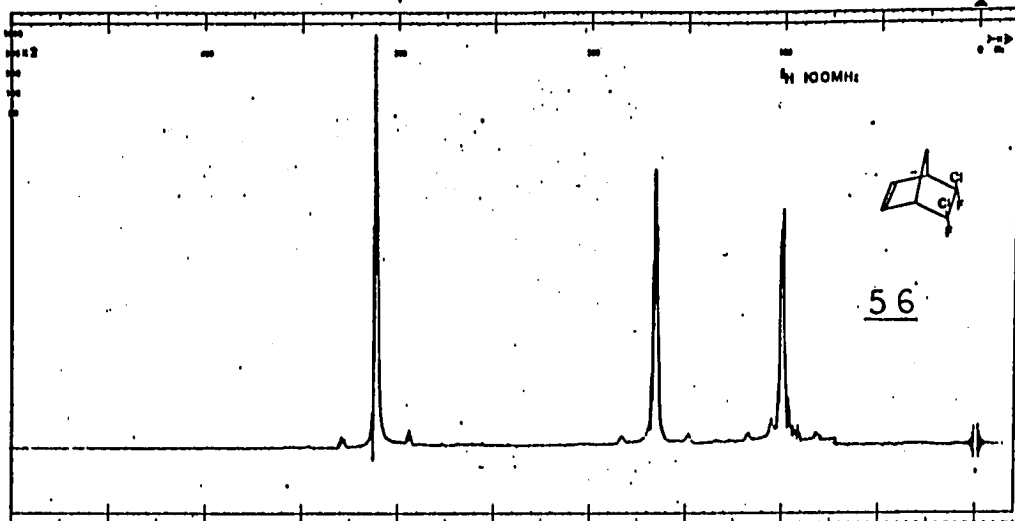
Attempted Cycloaddition of Butadiene to cis-Cyclooctene. Roughly 50 μ l of cis-cyclooctene were heated under nitrogen with 0.3 g of butadiene for 3 hr at 125°C. No materials with a retention time approximating that of the butadiene adduct with trans-cyclooctene could be detected on the vpc.

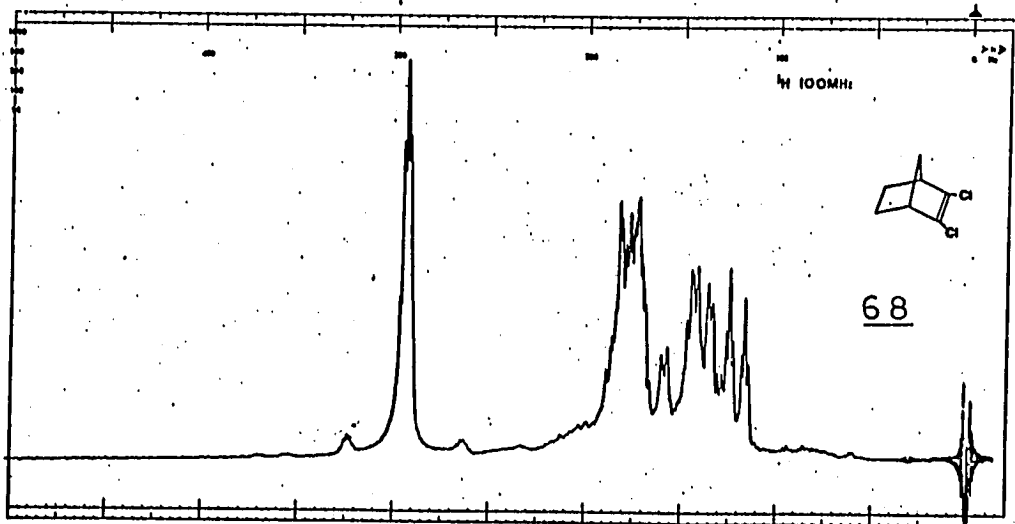
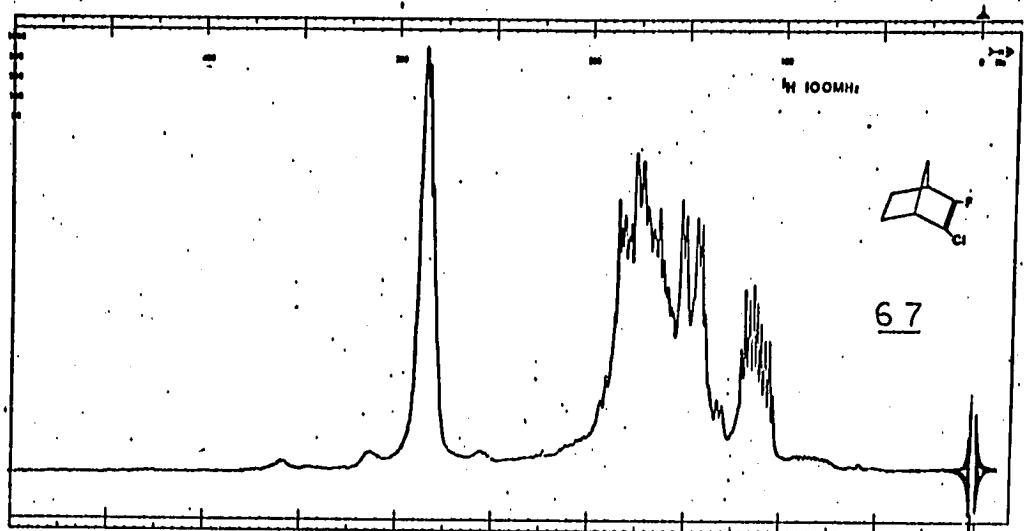
In a sealed tube under nitrogen 20 g of butadiene, 5 g of cis-cyclooctene, and a trace of hydroquinone were heated for 16 hr at 168°C. A heavy viscous solution with suspended solids resulted. Vpc analysis suggested that only traces of materials with the retention time of the butadiene adduct to trans-cyclooctene were present. The intractably viscous nature of the reaction mixture foiled attempts at isolation of these materials.

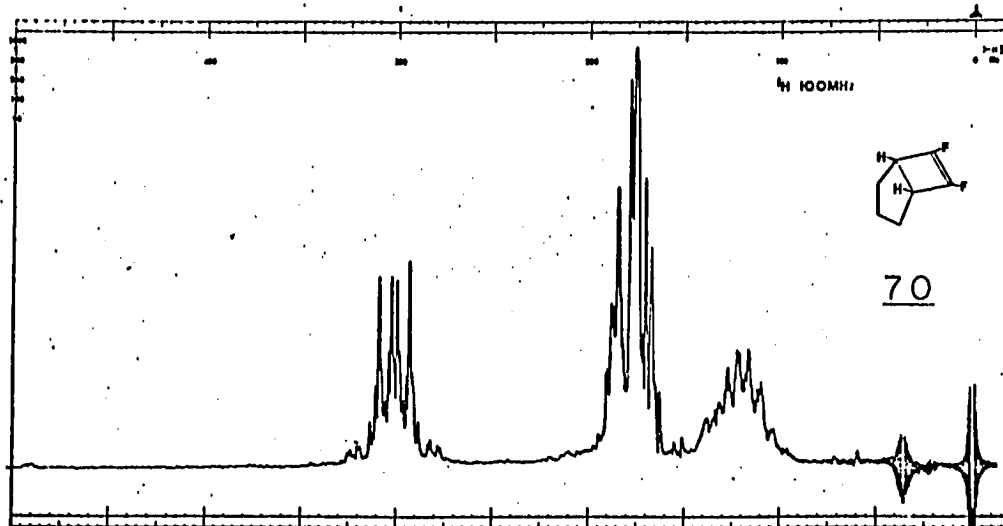
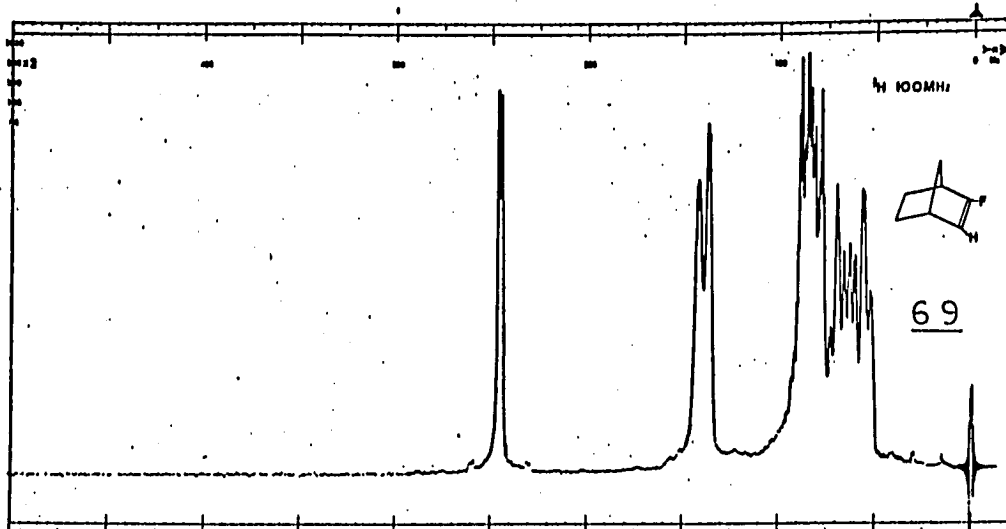


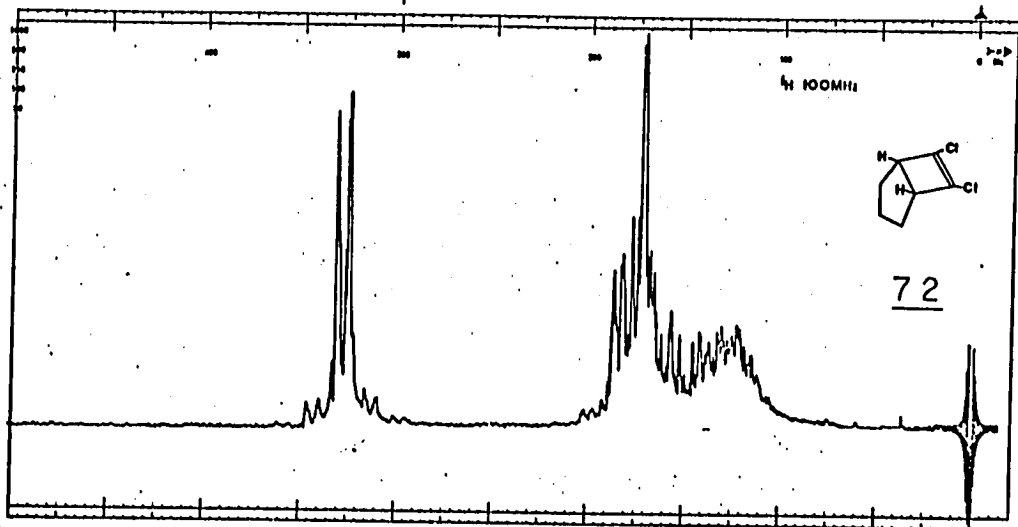
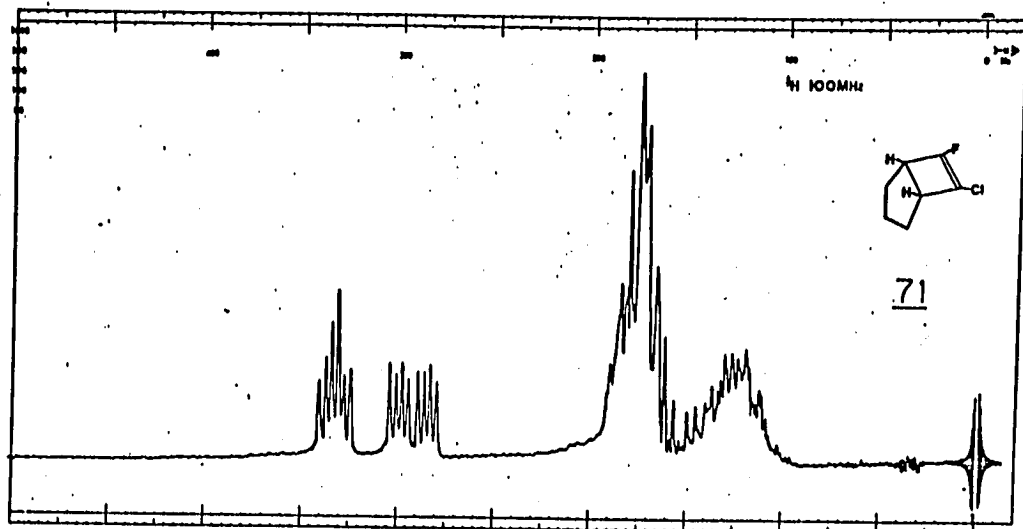


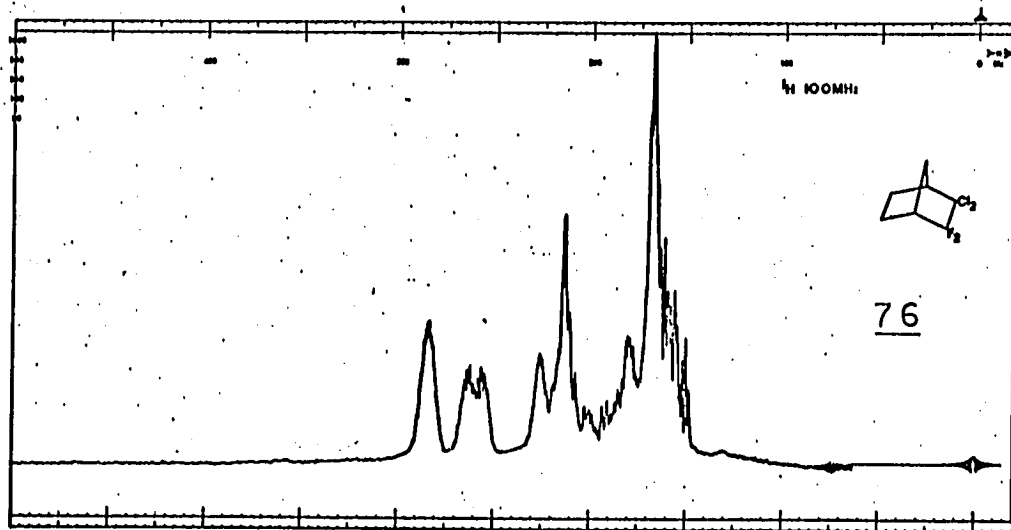
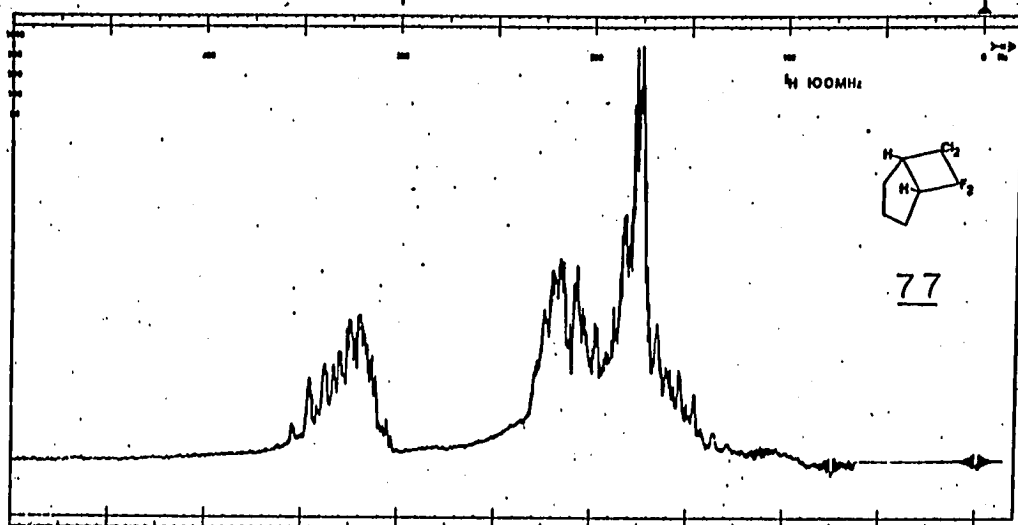


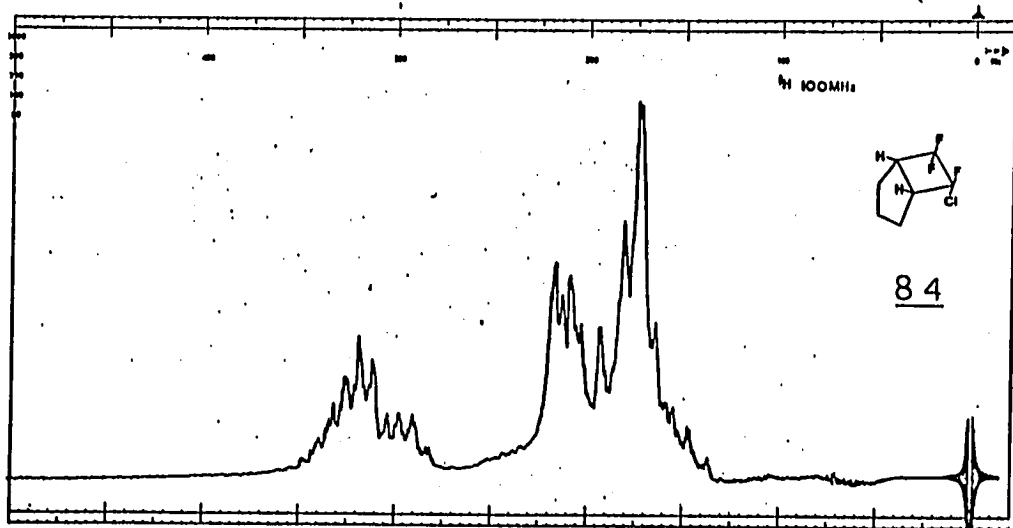
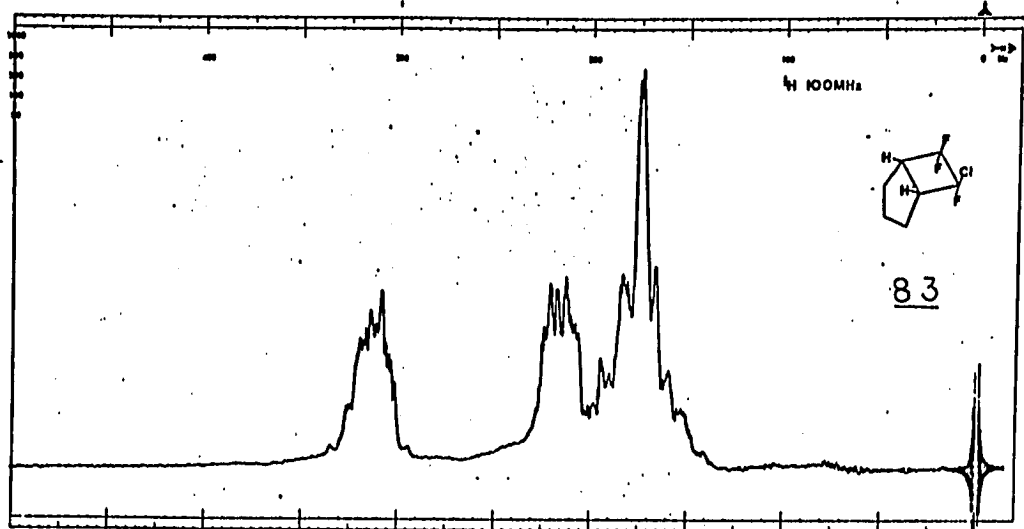


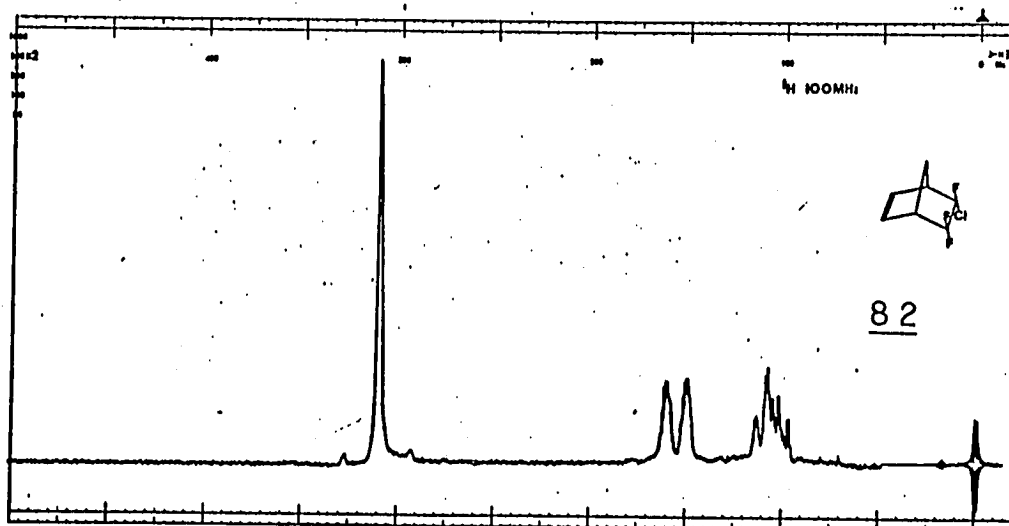
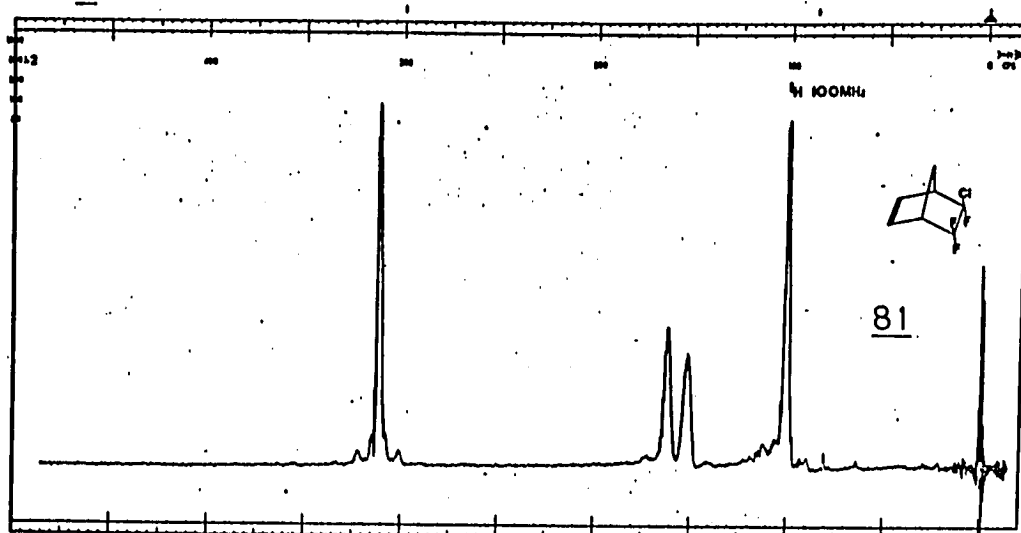


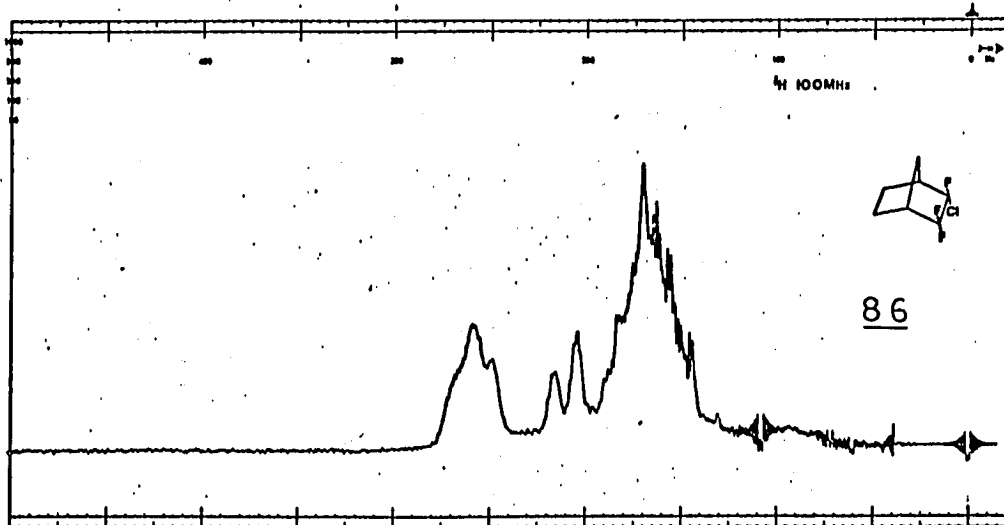
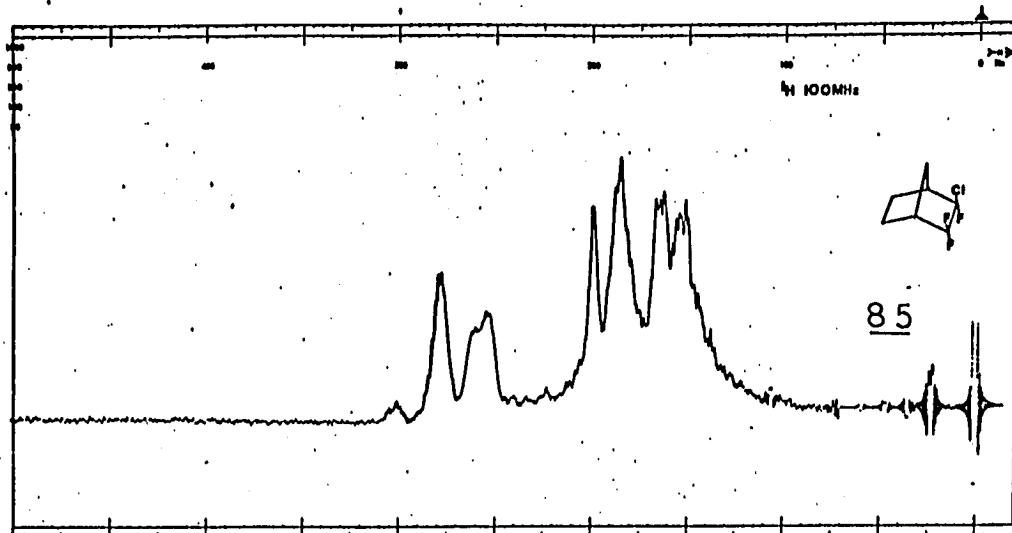


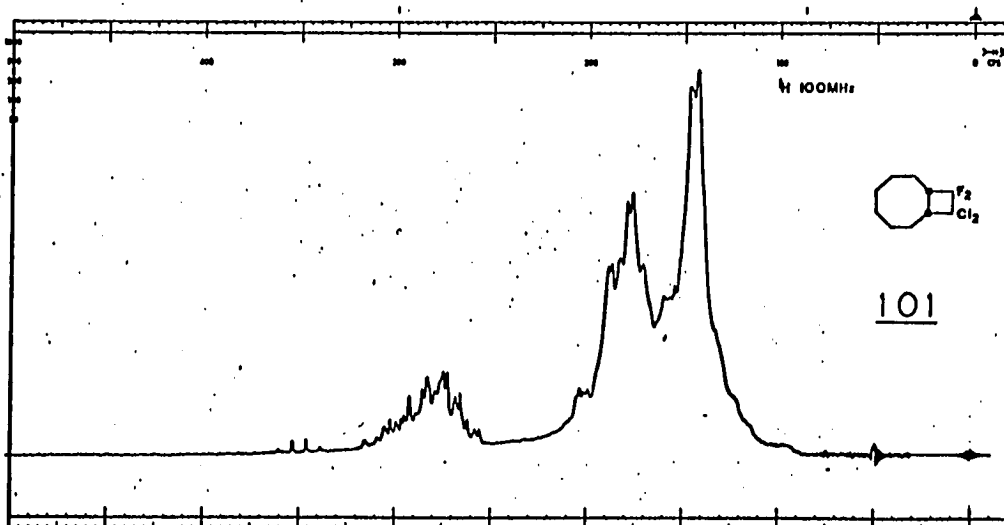
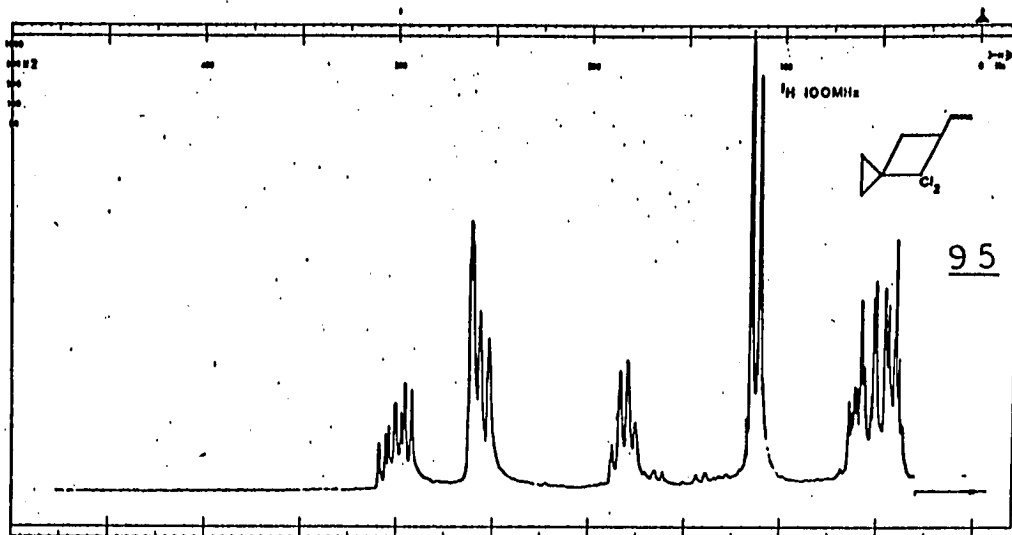


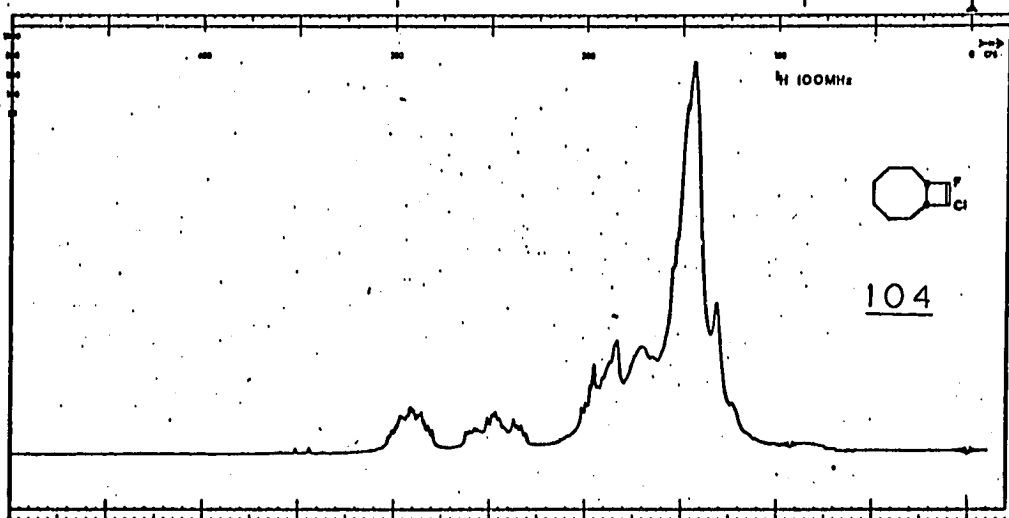
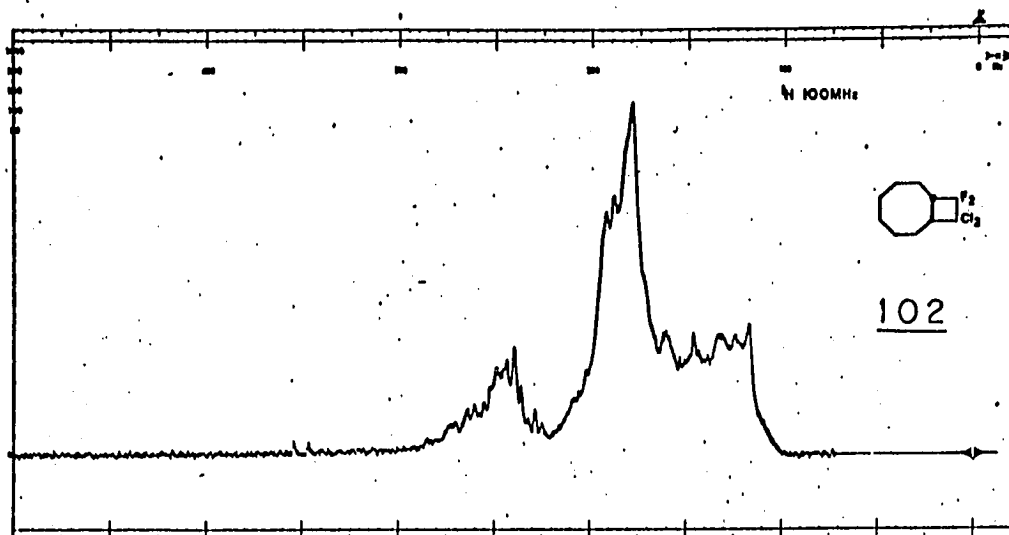


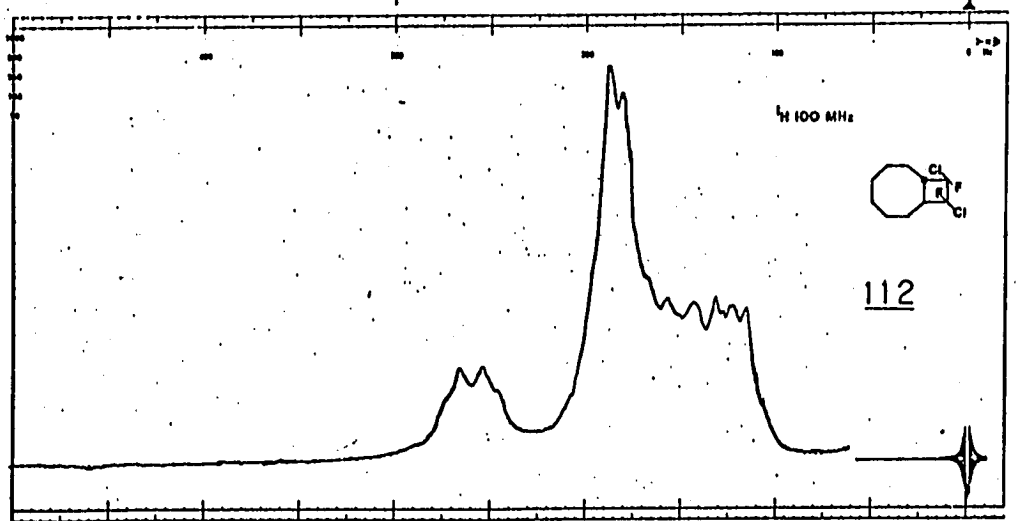
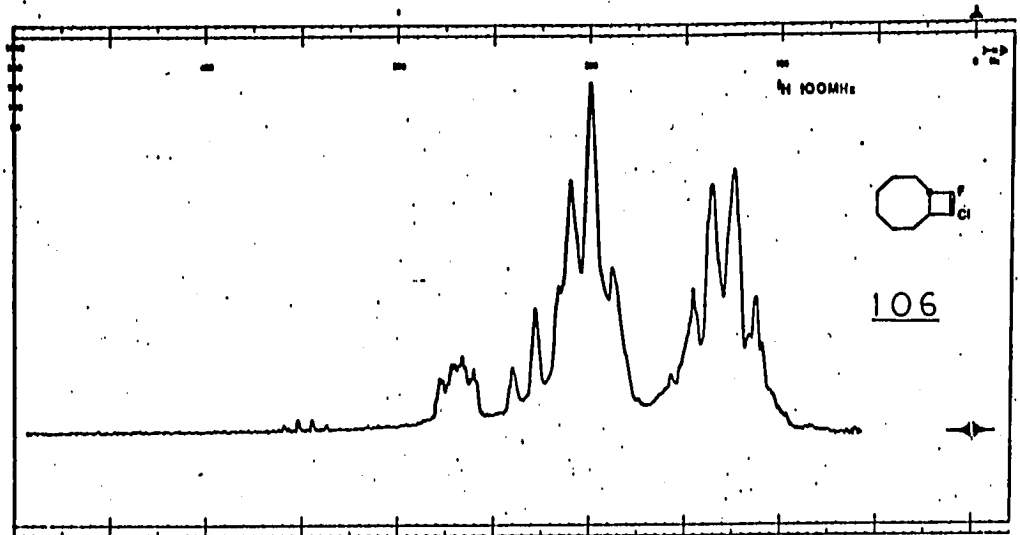


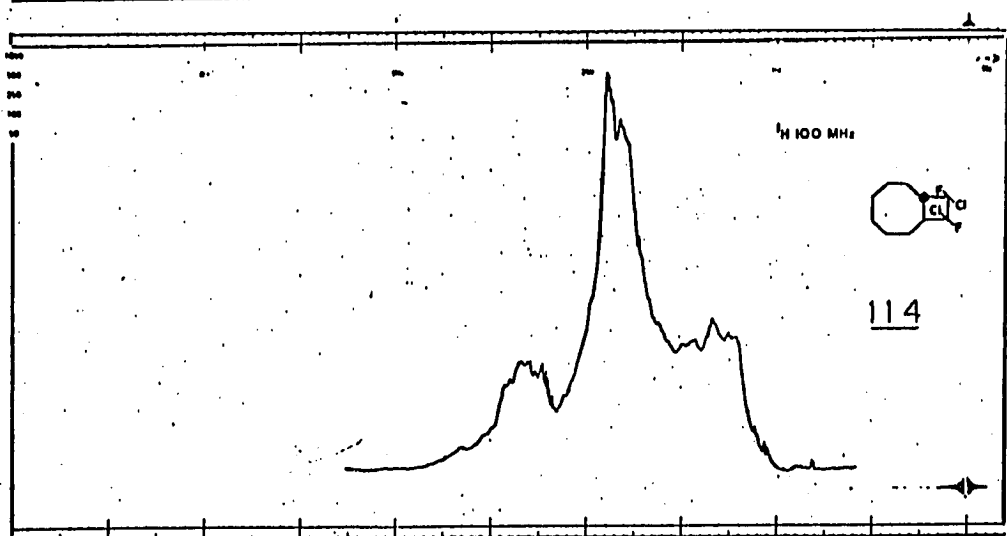
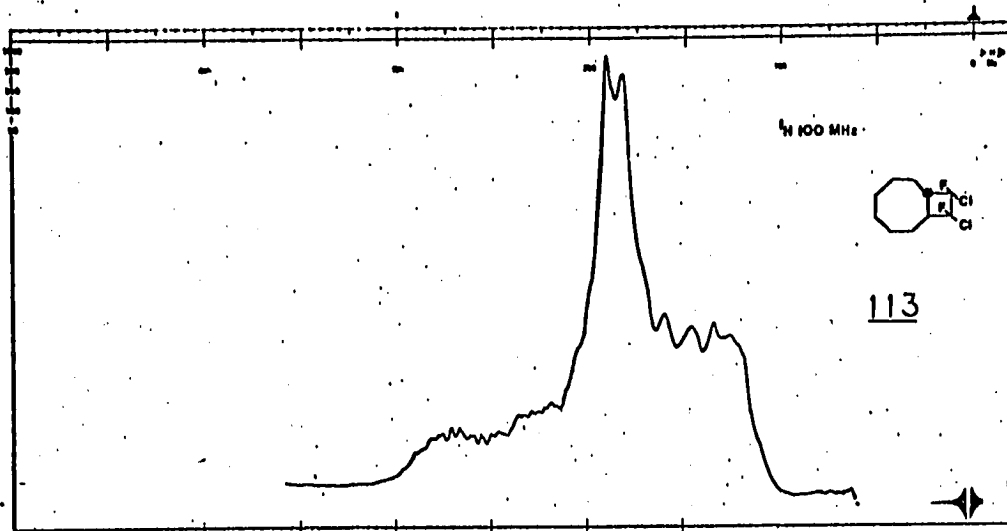


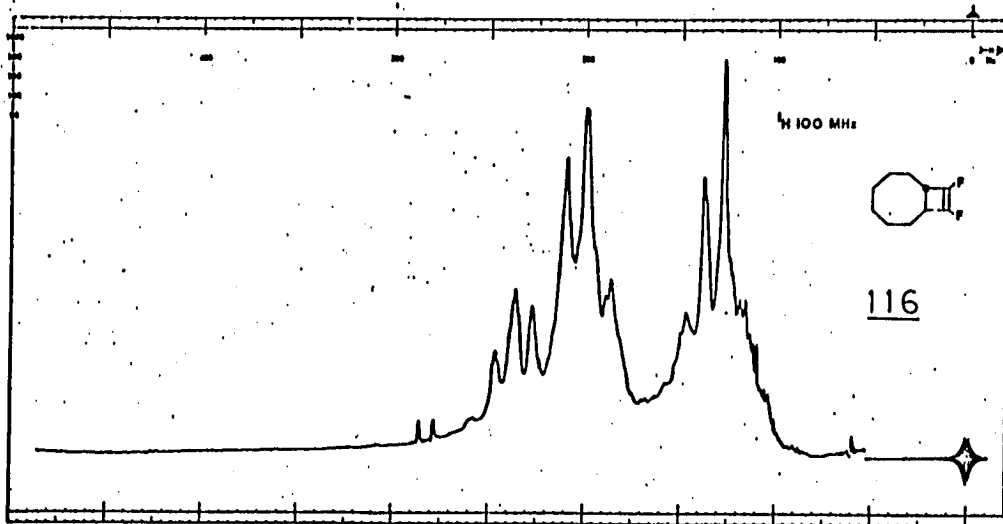
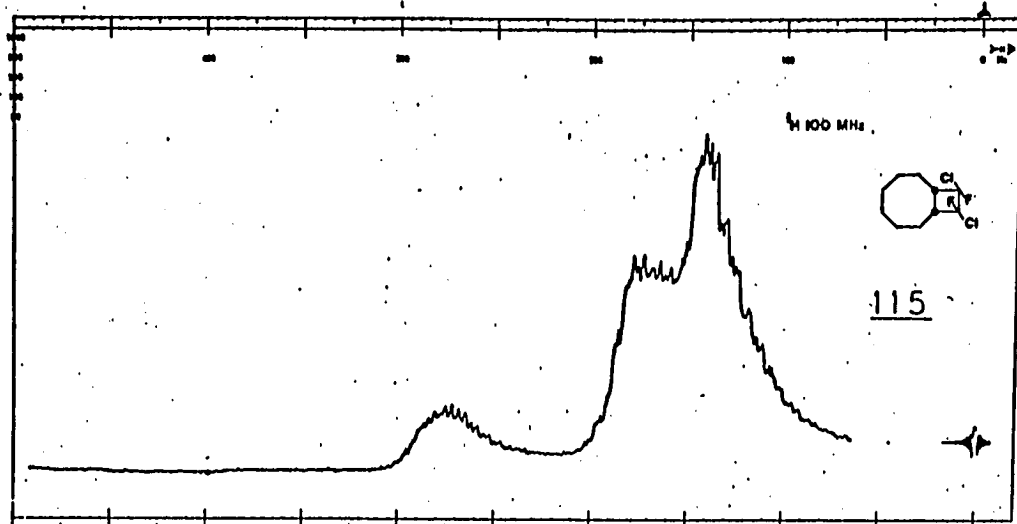


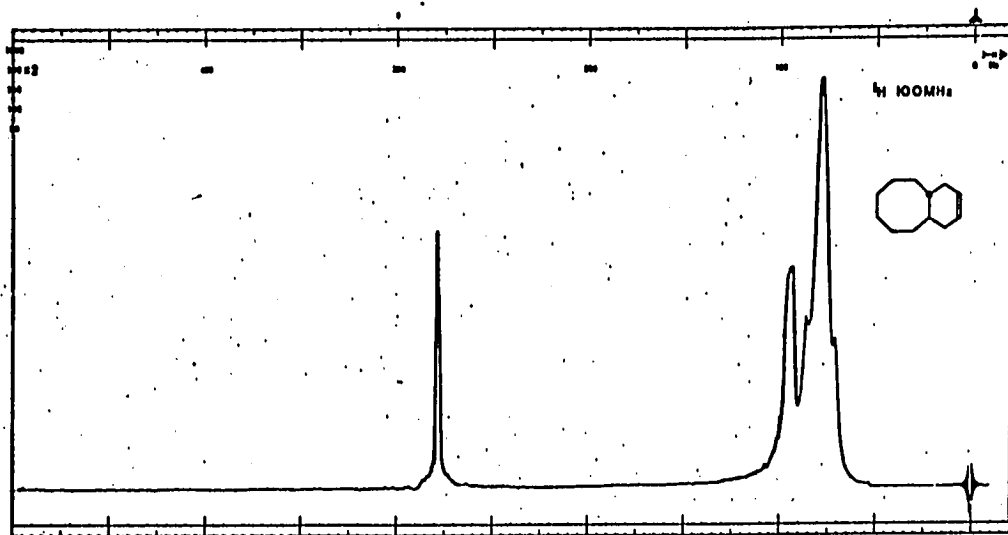




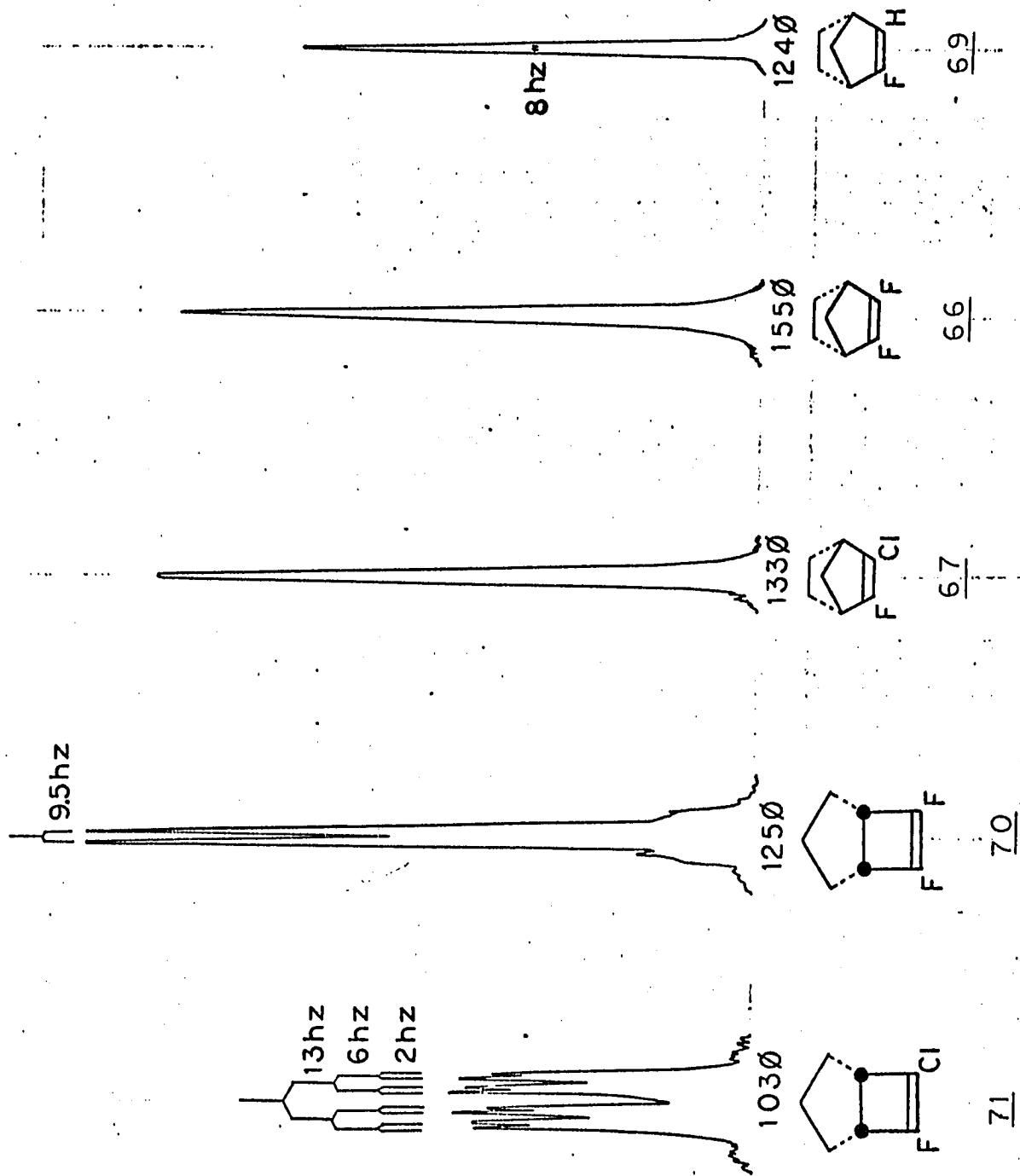




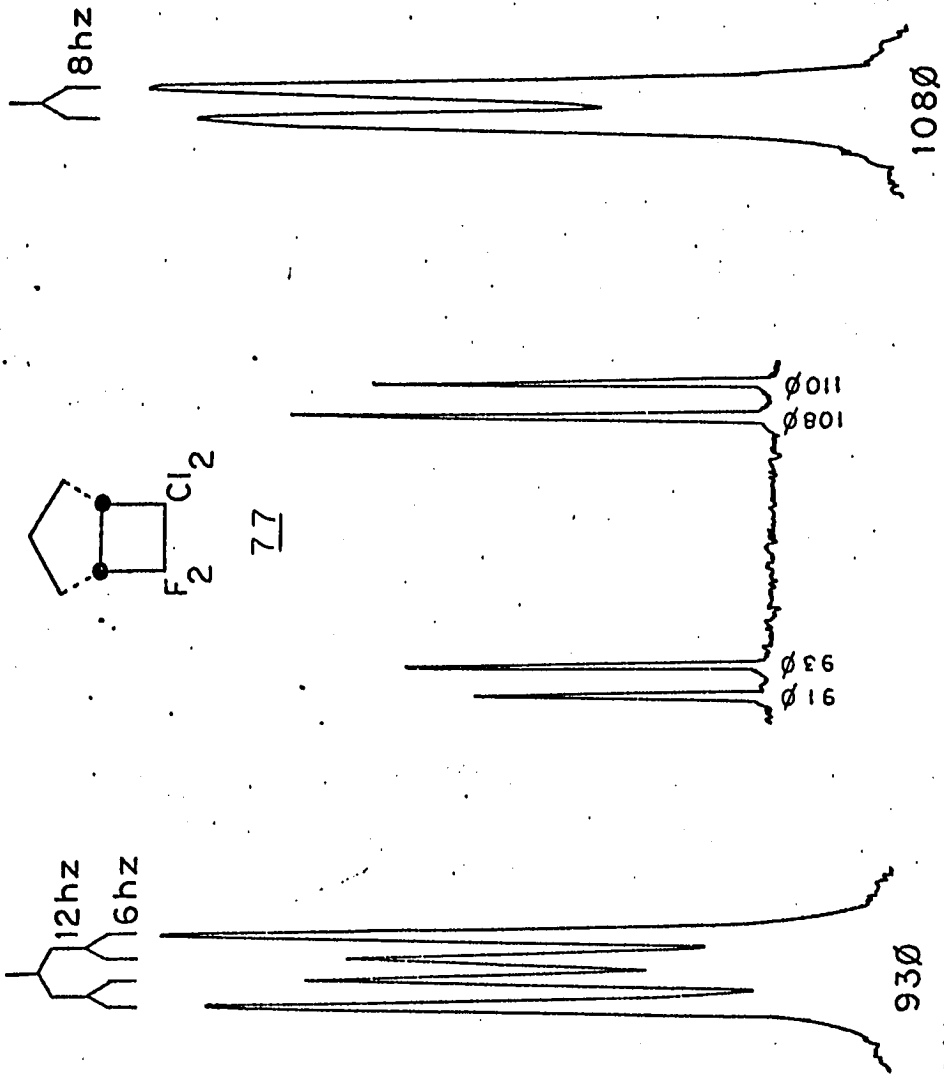


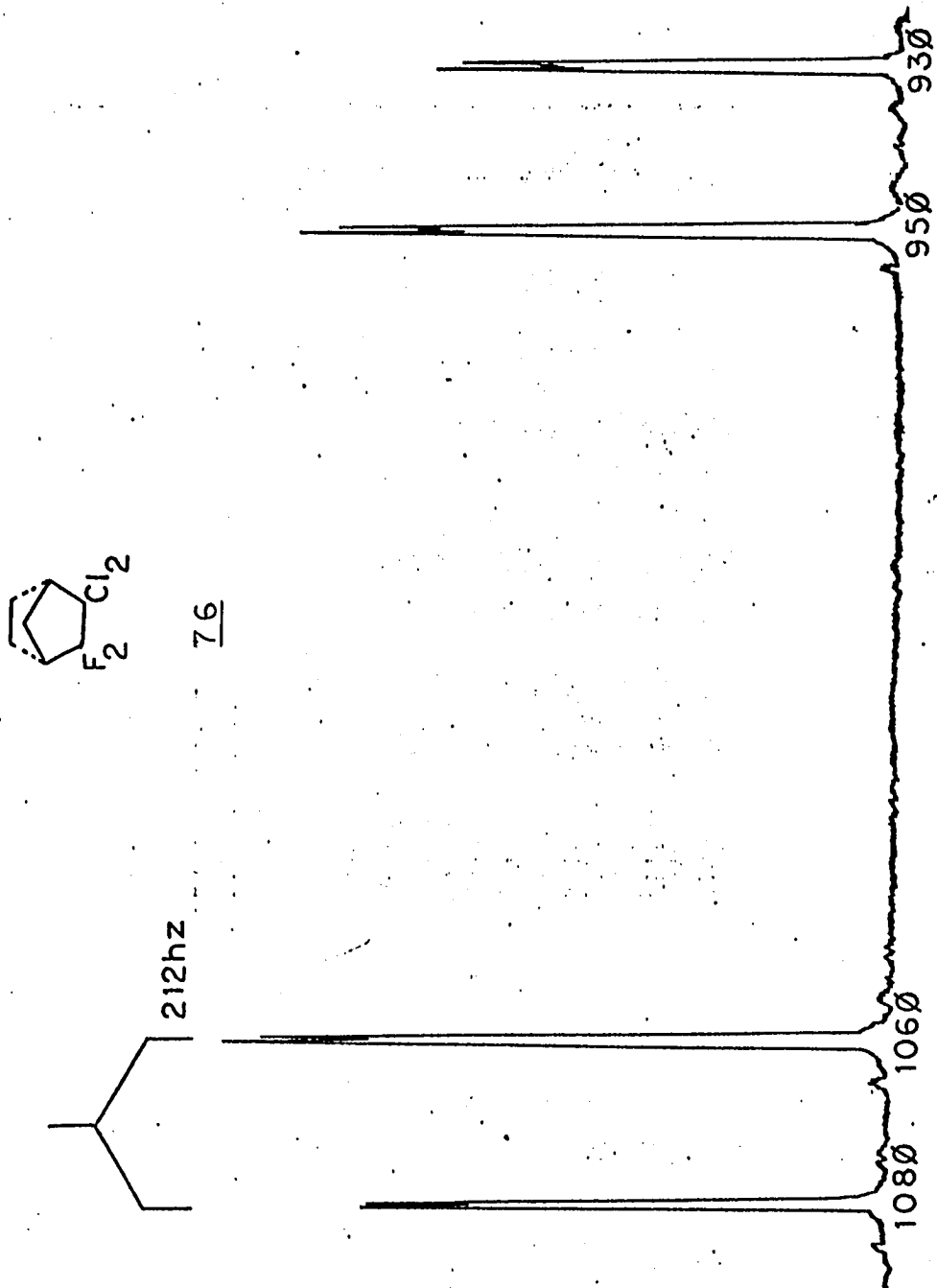


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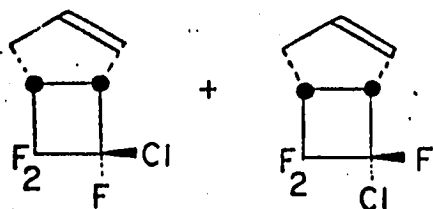


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^{19}F NMR 94.1Mhz

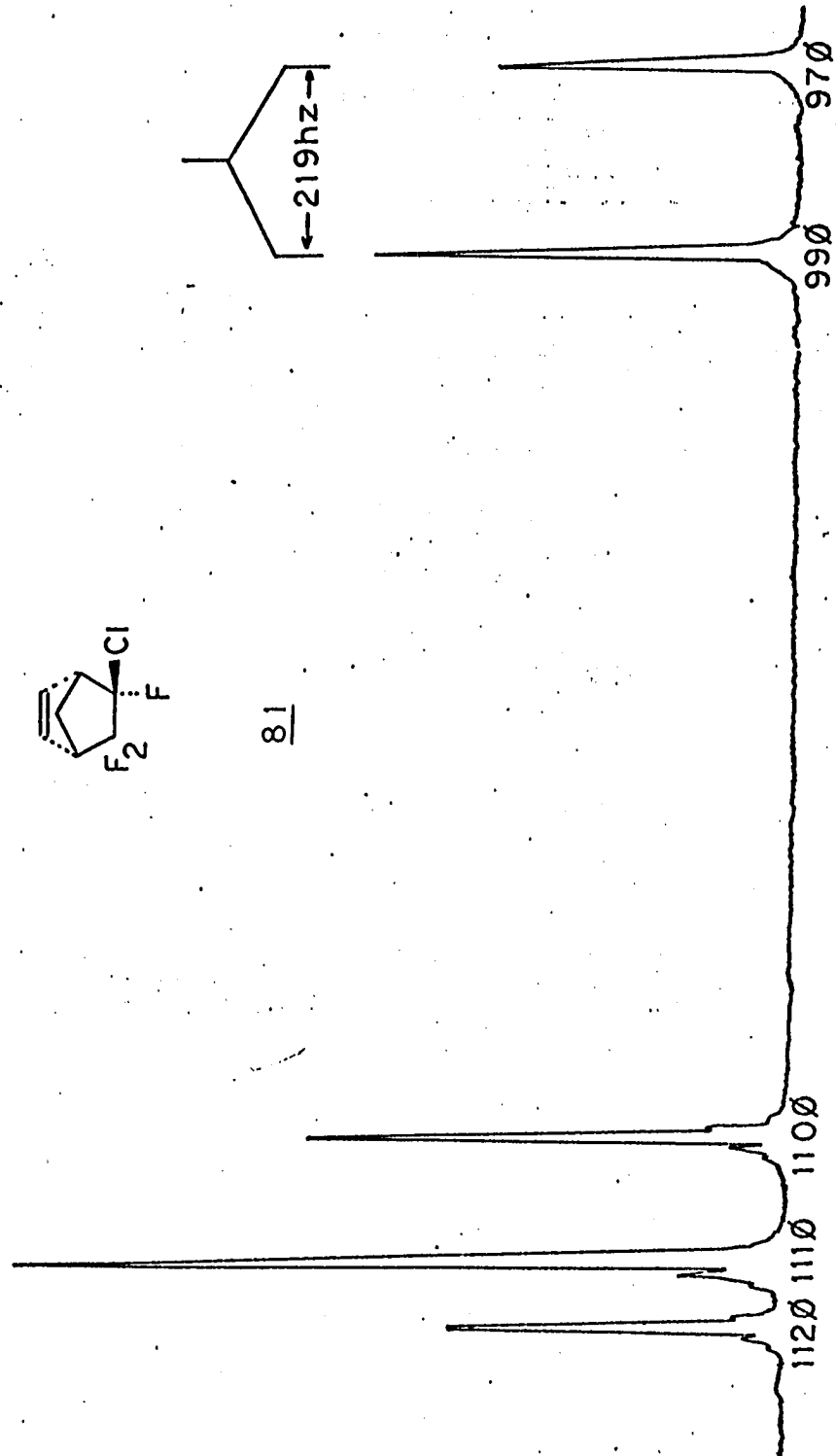
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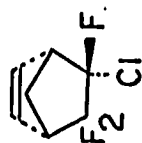
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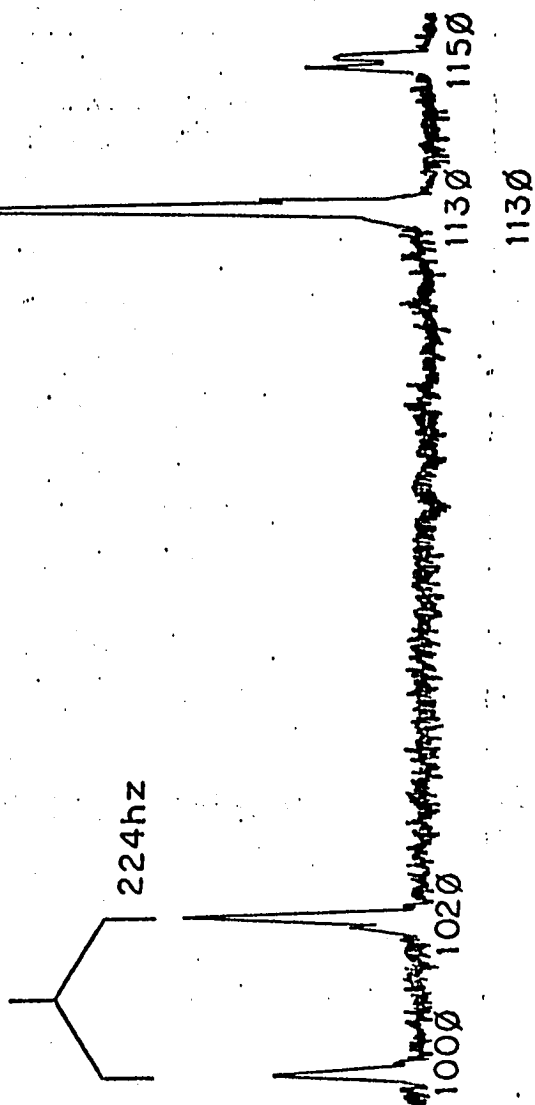


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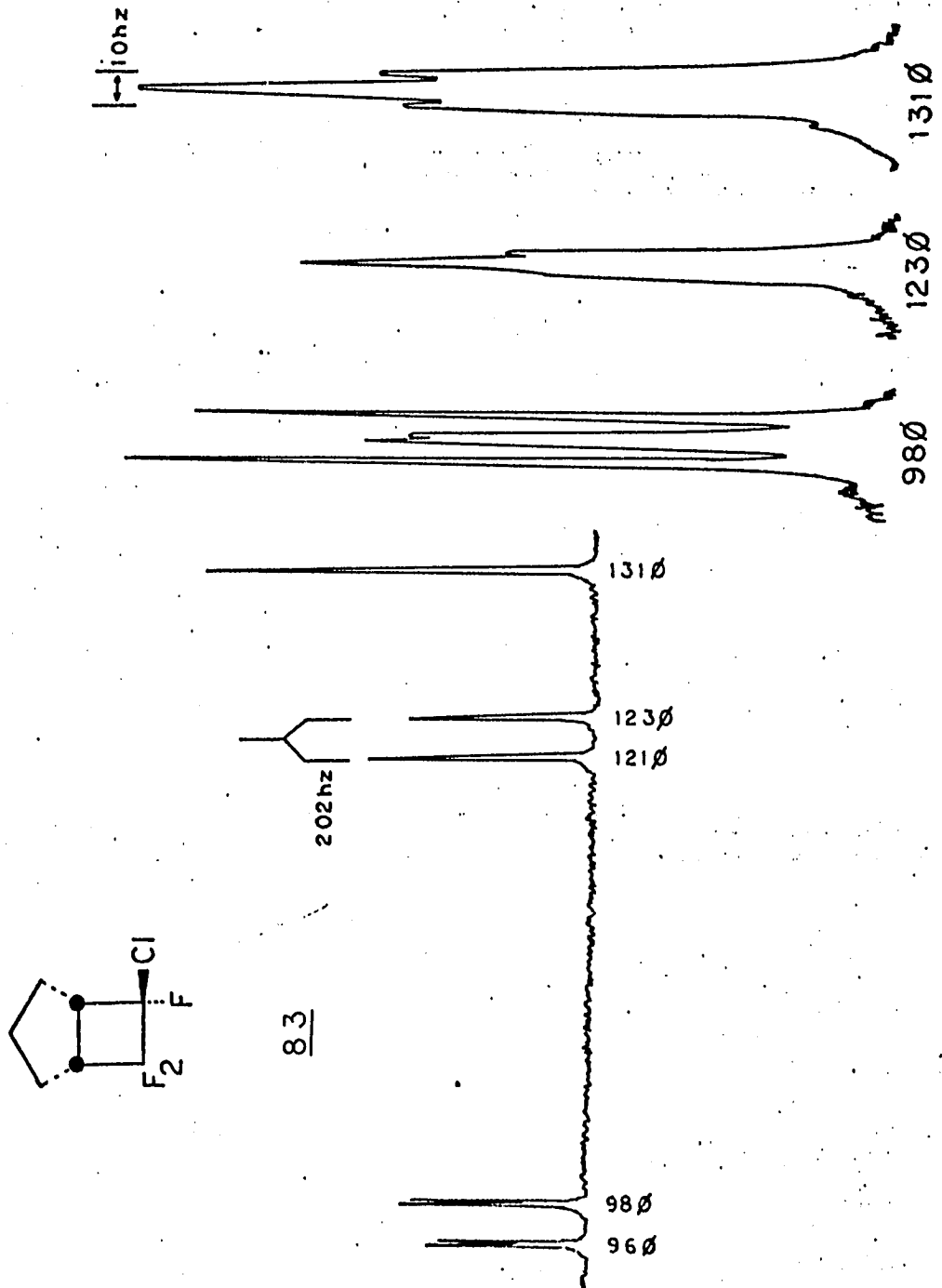
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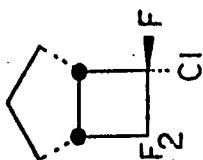
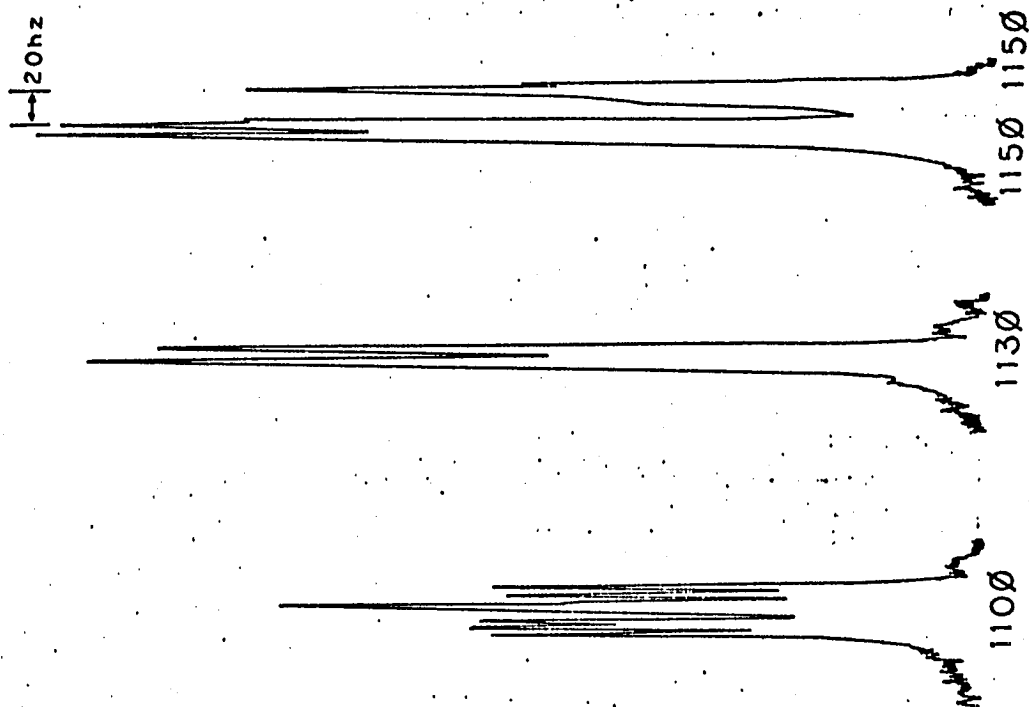
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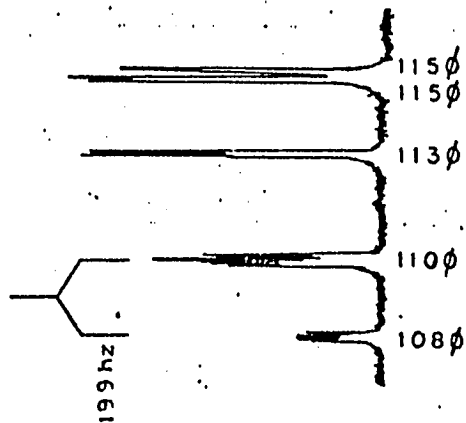
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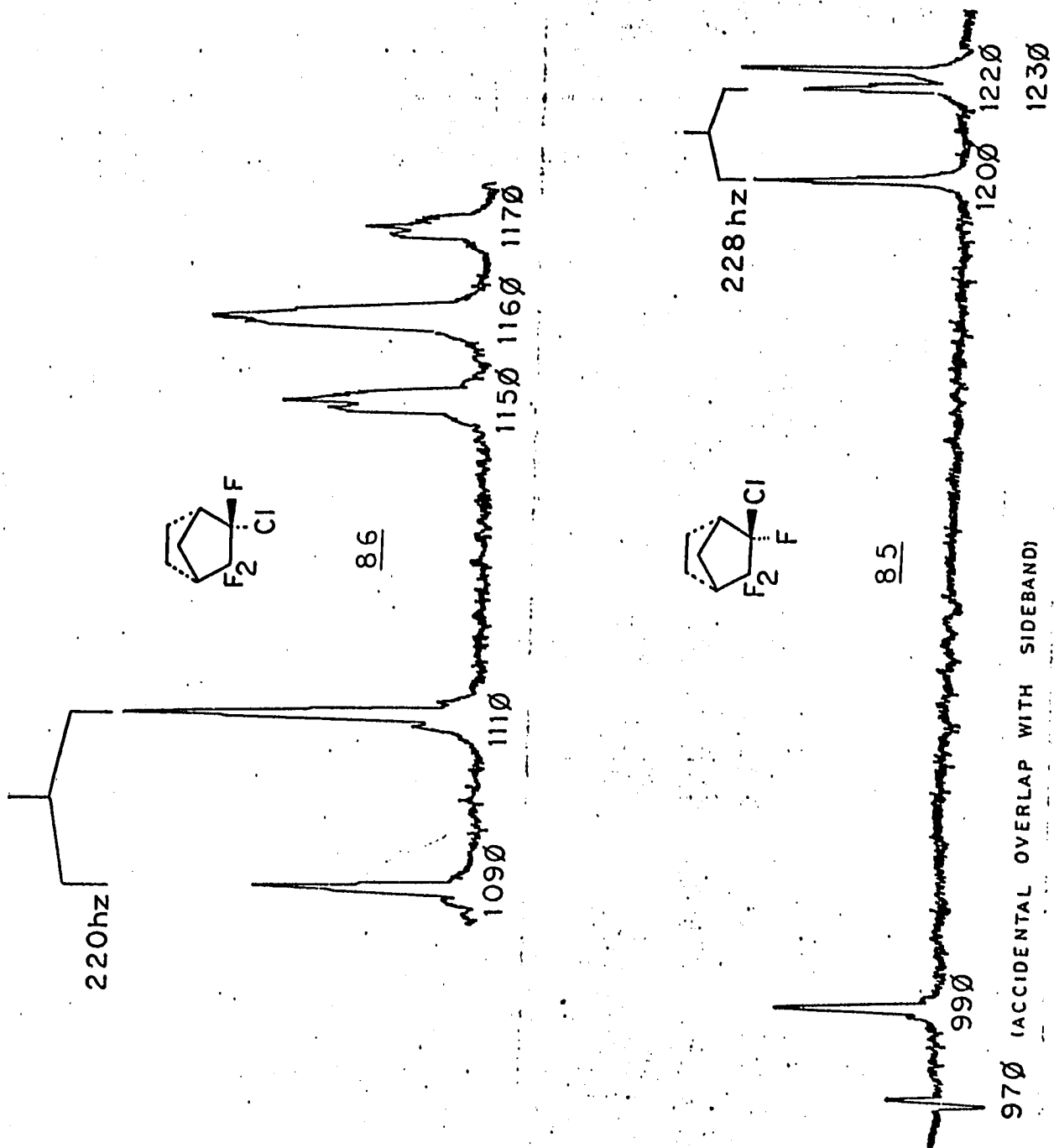
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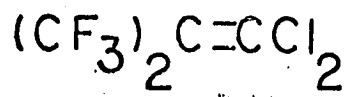
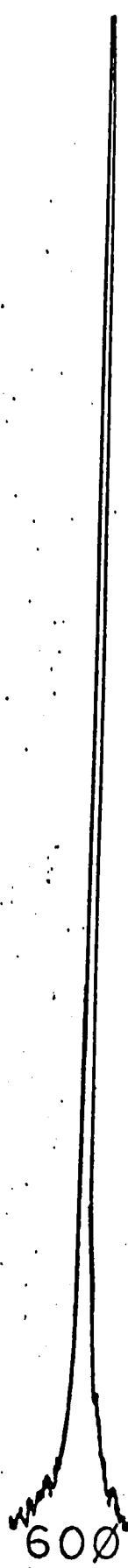


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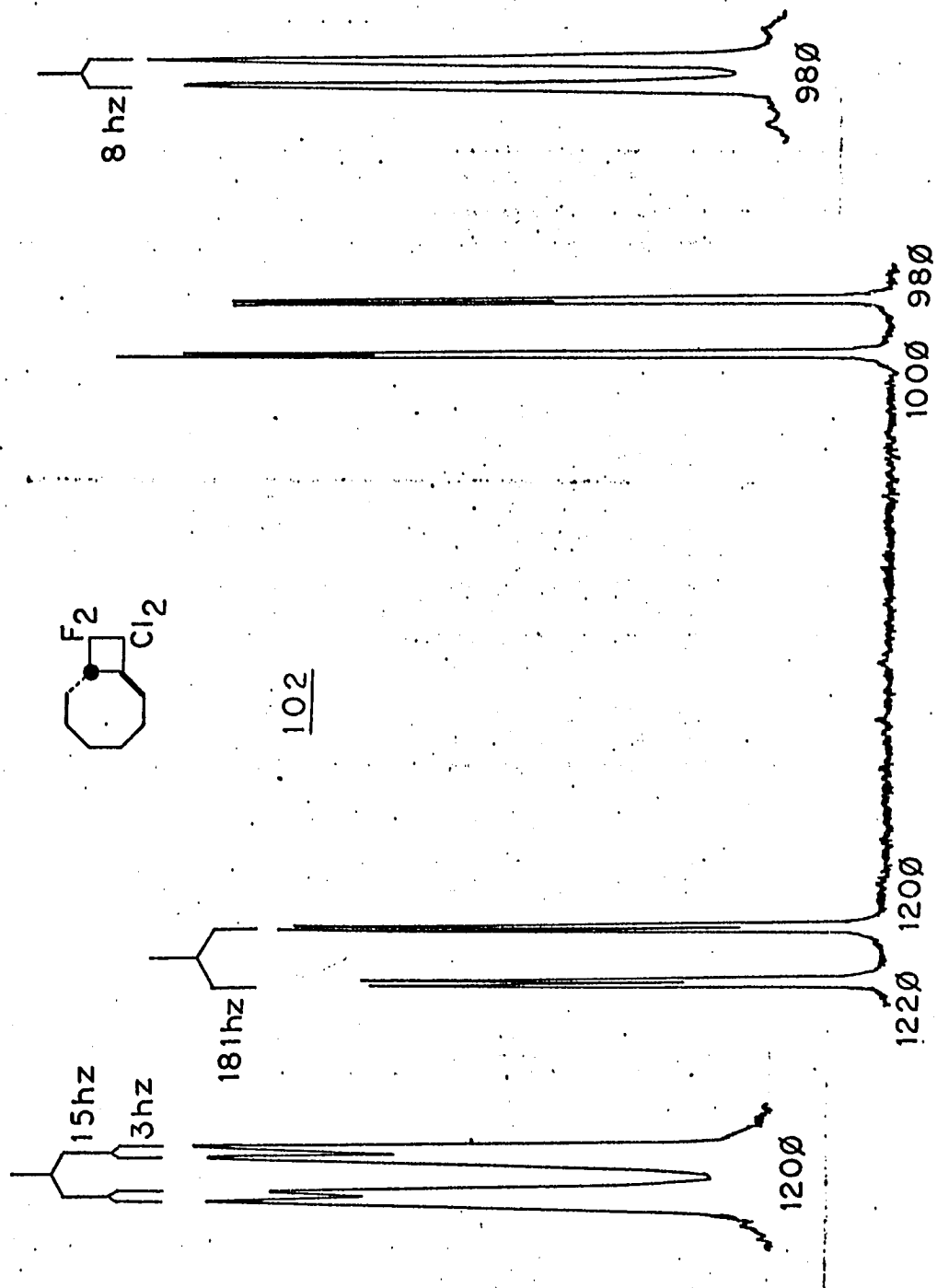
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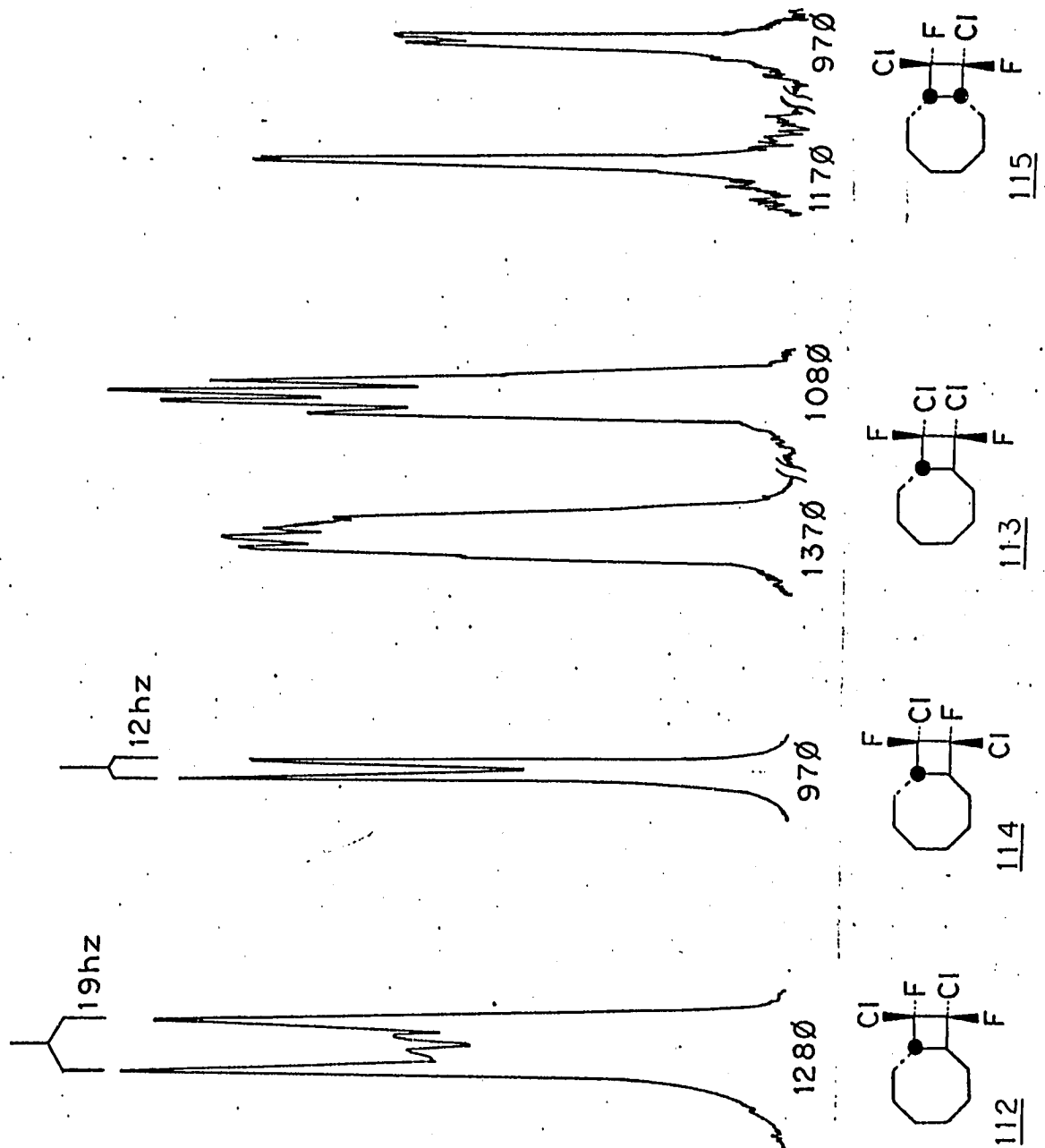


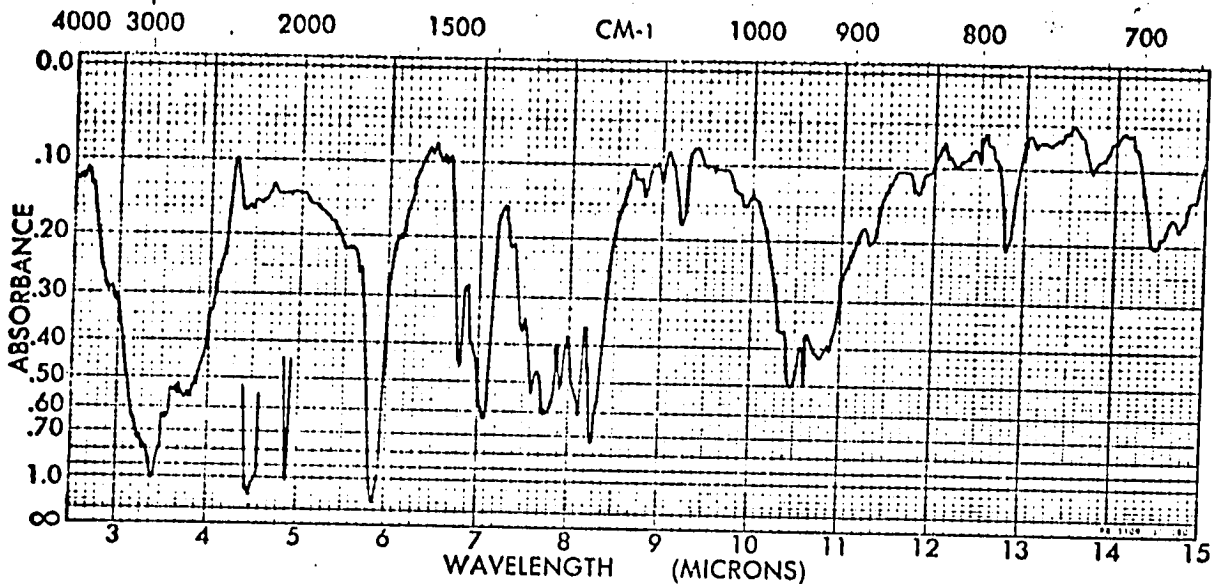
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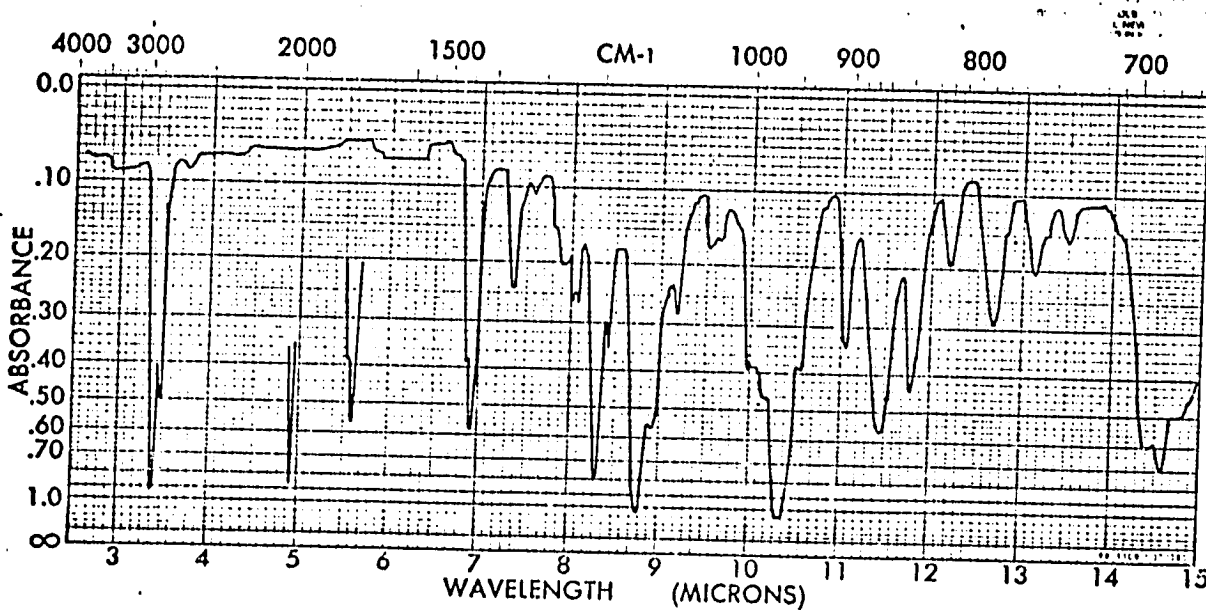


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	THICKNESS	OPERATOR	

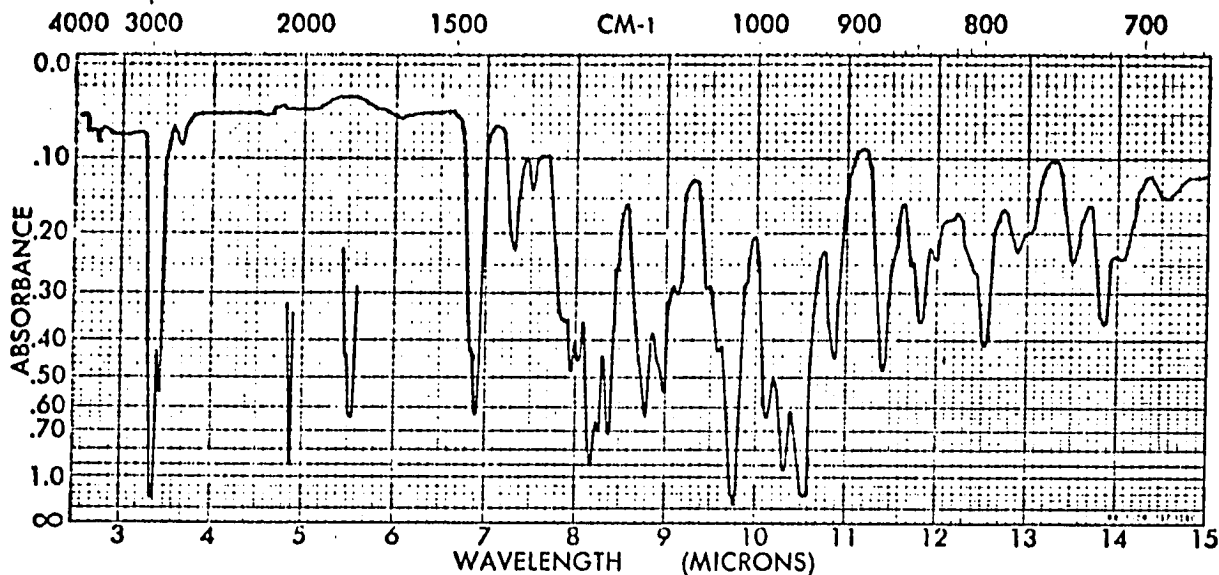
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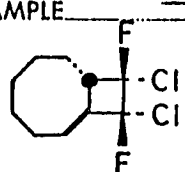


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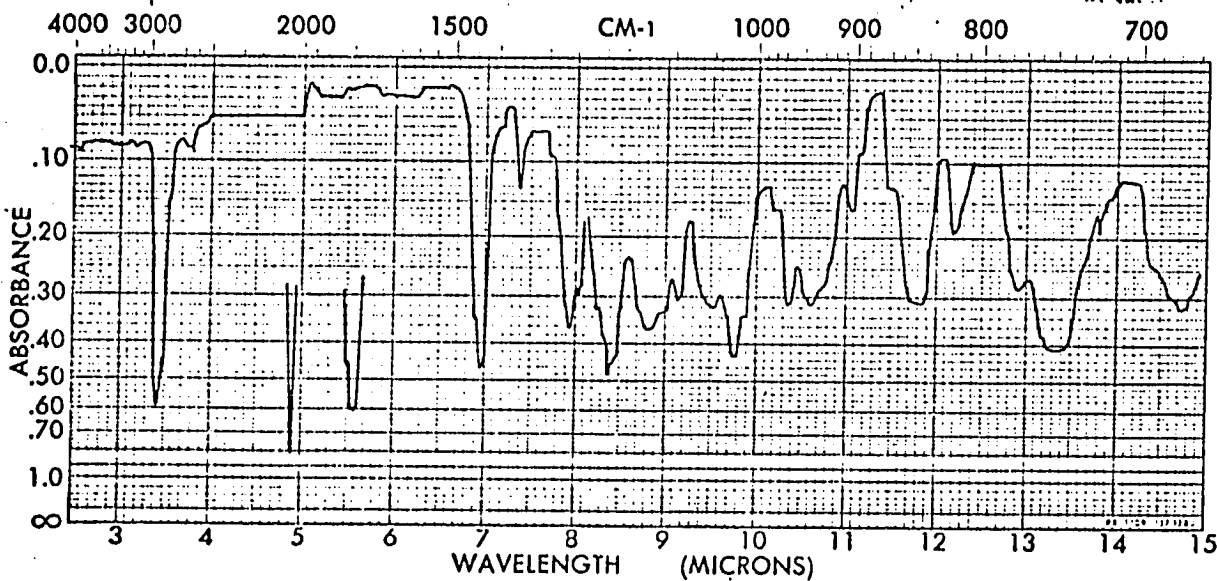
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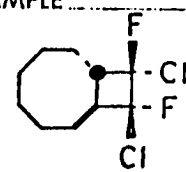
RECORDING CHARTS:
LALPHY & LINDNER'S CORPORATION
BRIDGE PLAZA, NEW YORK
NEW YORK, N. Y. 10019



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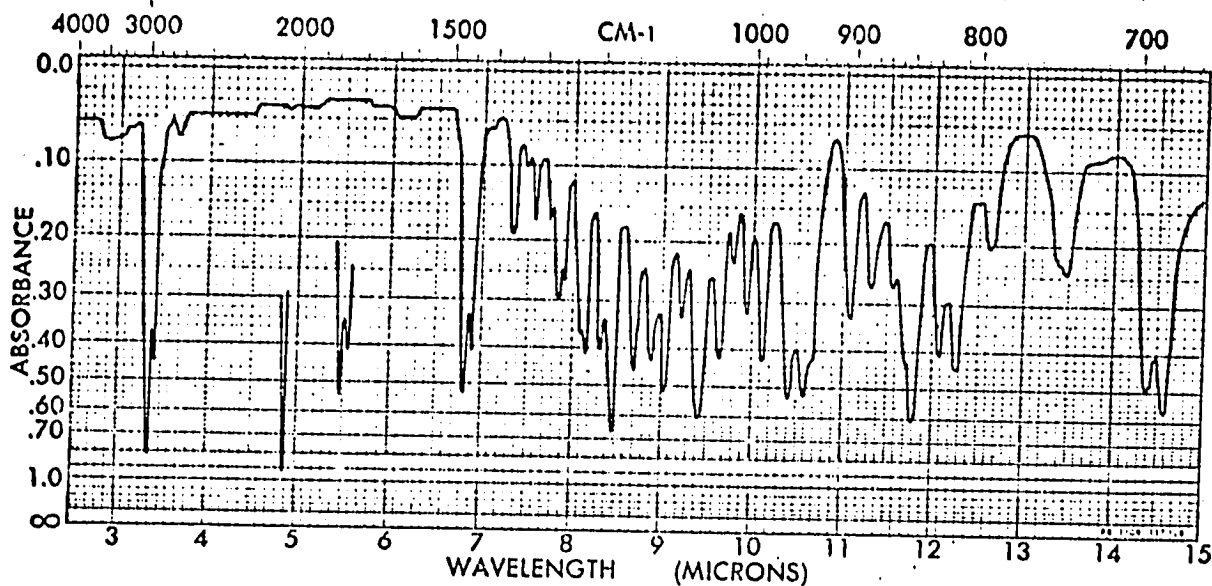
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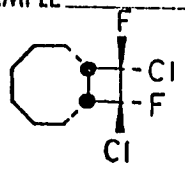


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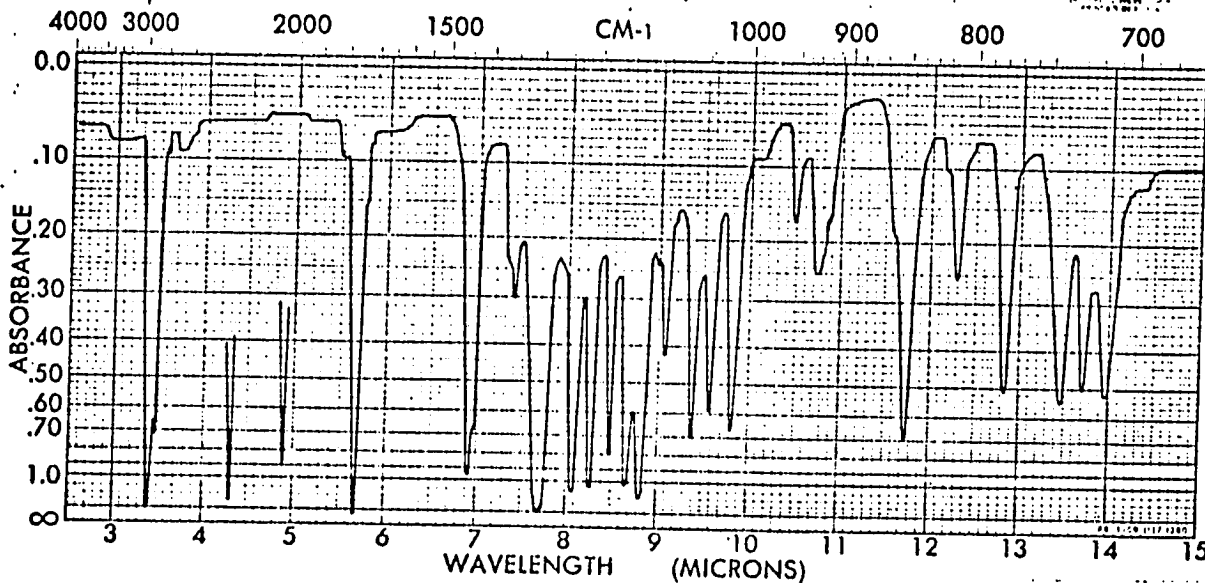
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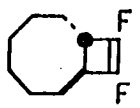
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GRAPHIC SYSTEMS CORPORATION
BUFFALO, NEW YORK
PRINTED IN U.S.A.



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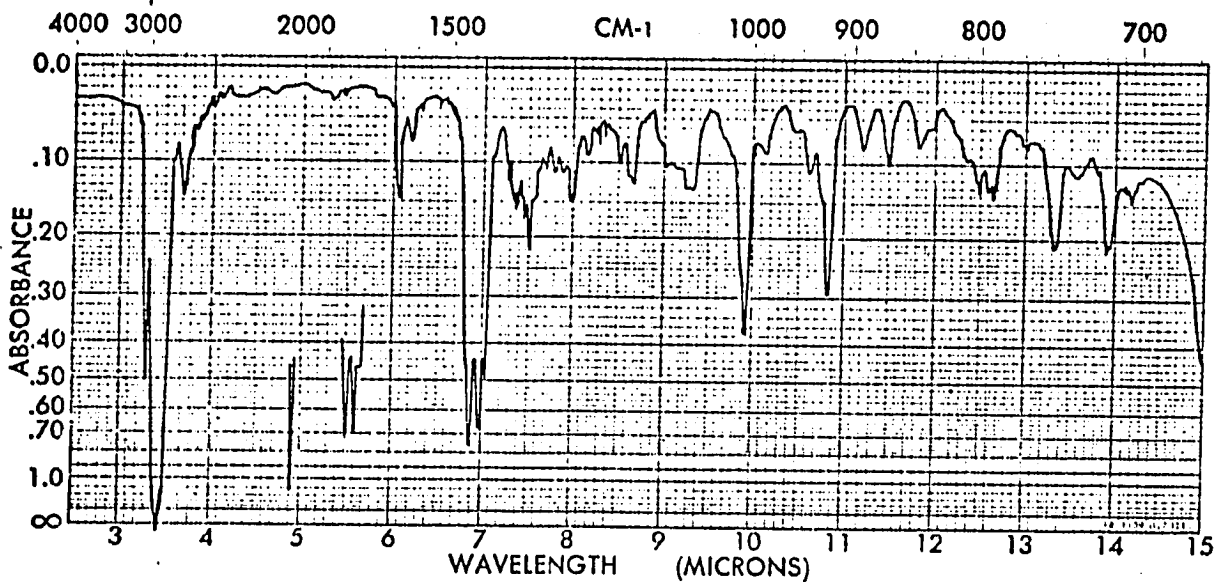
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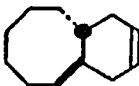


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SPECTRUM NO. SAMPLE

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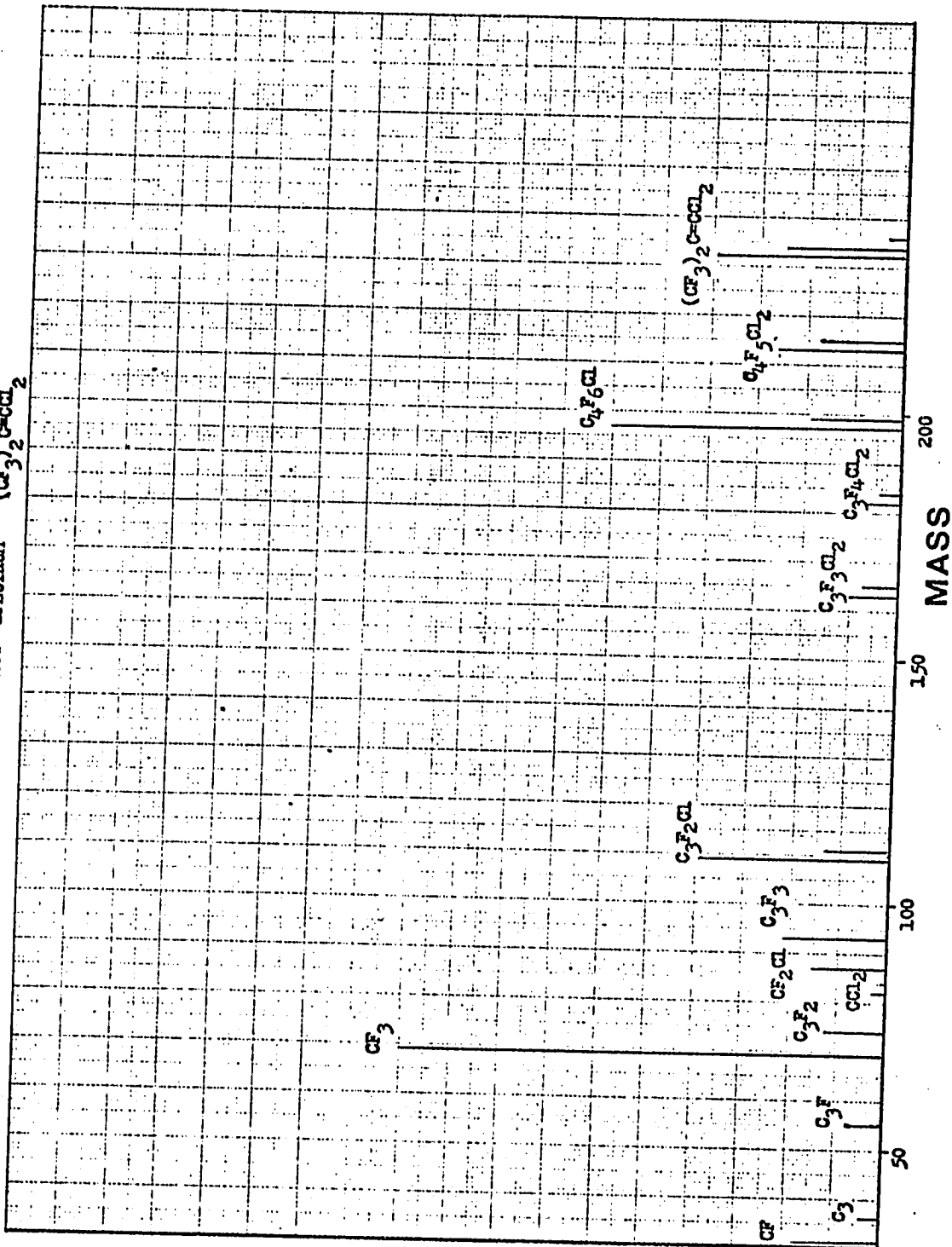
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	PHASE Neat	DATE	
	THICKNESS	OPERATOR	

SPECTRUM NO. SAMPLE

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GRAPHIC CONTROL CORPORATION
BUFFALO, NEW YORK
PRINTED IN U.S.A.

K₂Z 10 X 10 TO THE CENTIMETER 46 1521
10 X 25 CM.
MUEFFEL & ESSER CO.

MASS SPECTRUM (CF₃)₂C=CCl₂



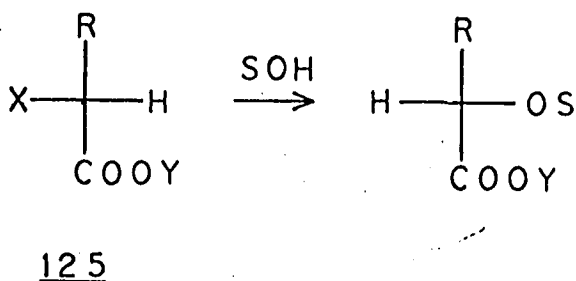
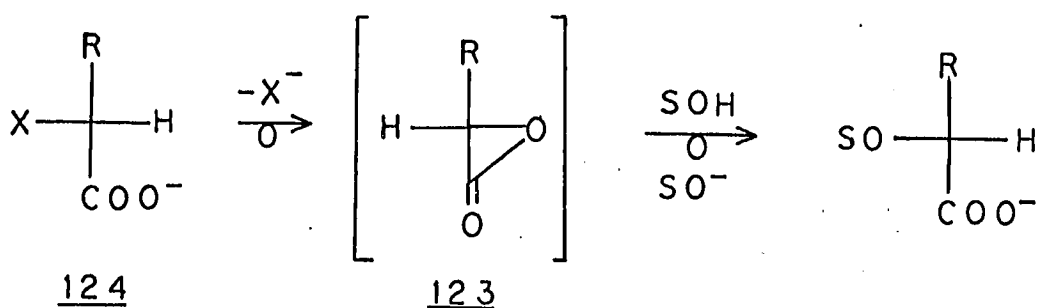
RELATIVE INTENSITY

α-Lactone Chemistry

VI. Motivation and Historical

A. α-Lactones as reaction intermediates

α-Lactone intermediate 123 has been invoked principally to account for the fact that 124 solvolyses with overall retention of configuration whereas the corresponding 125 solvolyses with inversion of configuration:¹³¹



X = Br, OTs, N₂⁺

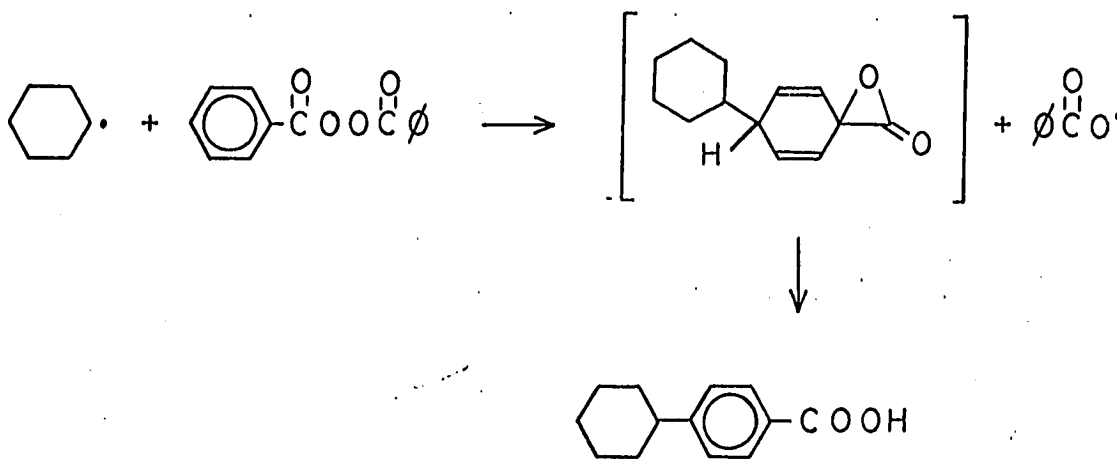
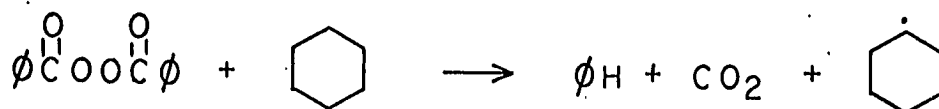
Y = H, OMe, OEt, NHCH₂COOH

R = φ, CH₃

SOH = HOH, MeOH

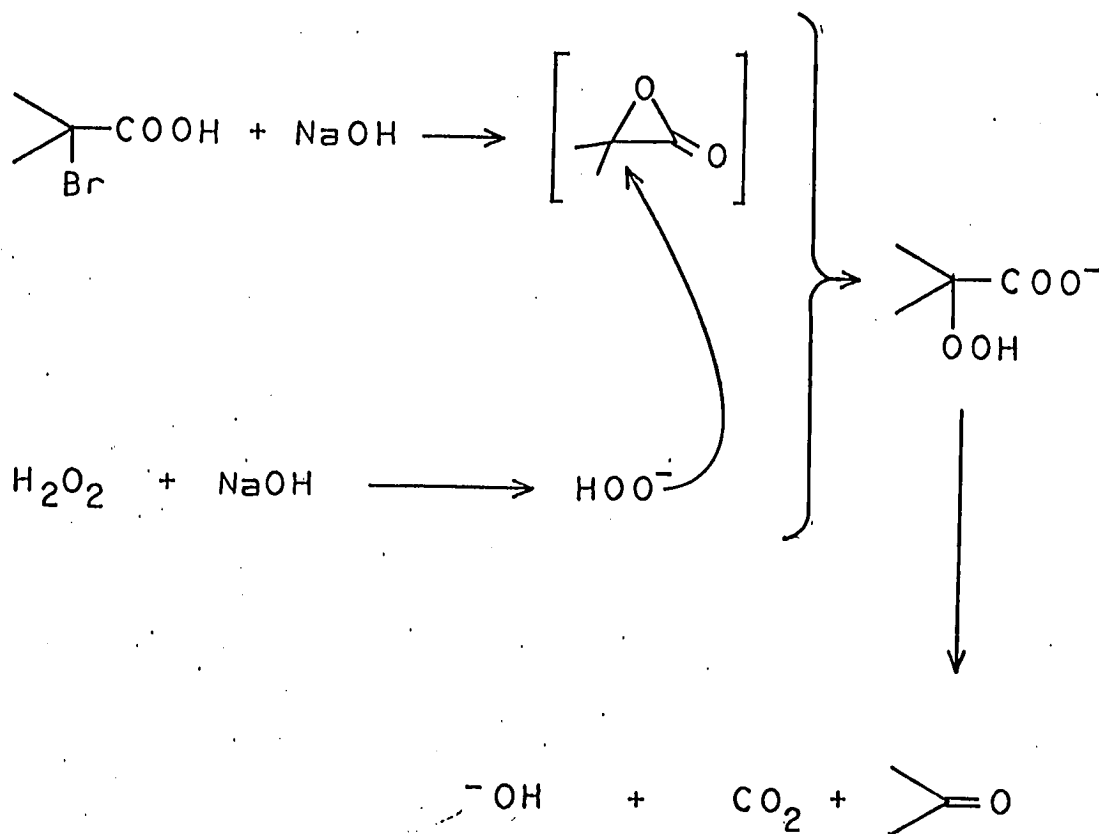
131. a/ C. M. Bean, J. Kenyon, and H. Phillips, J. Chem. Soc., 303 (1936). b/ C. K. Ingold, Structure and Mechanism in Organic Chemistry, Second Edition, Cornell University Press, Ithaca, New York, 1969, pp. 520-535. c/ W. A. Cowdrey, E. D. Hughes, and C. K. Ingold, J. Chem. Soc., 1208(1937). d/ E. Grunwald and S. Winstein, J. Am. Chem. Soc., 70, 841(1948). e/ J. Kenyon and H. Phillips, Trans. Faraday Soc., 26, 451(1930).

In studying the thermal decomposition of benzoyl peroxide in cyclohexane, Walling has postulated that ortho- and para-cyclohexylbenzoic acids arise by an induced decomposition through α -lactone intermediates,¹³⁵



135. C. Walling and E. S. Savas, J. Am. Chem. Soc., **82**, 1738(1960).
See also J. E. Leffler and R. G. Zepp, J. Am. Chem. Soc., **92**, 3713(1970).

Wright has proposed the involvement of α -lactones in the formation of ketones on the reaction of α -bromoacids with basic hydroperoxides,¹³⁶

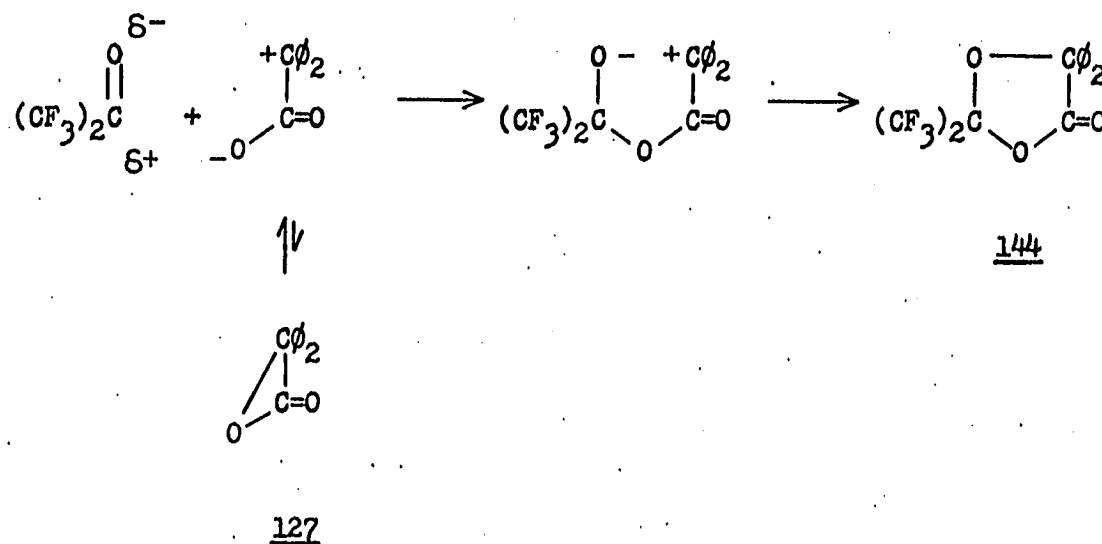


α -Lactonoid intermediates rationalize the rearrangement of aromatic peroxides to carbonates.¹³⁷

136. J. M. Wright, Ph. D. Thesis, Harvard U., 1967.

137. D. B. Denney, J. Am. Chem. Soc., 78, 590(1956).

While a detailed consideration of this value of 6 kcal/mole would be foolhardy, several points become clearer. The open and closed forms of an α -lactone, 133 and 135, may very well be of similar energy. If this is the case, the carbonium ion center in 135 which bears a nearly full positive charge is the key to α -lactone stability and reactivity. If the carbonium ion center is unaffected by substituents on carbon, an α -lactone briefly stable at low temperatures is expected. Indeed this seems to be the case for di-*t*-butylacetolactone (see below). On the other hand as resonance stabilization at the carbonium ion center becomes increasingly effective, the dipolar ion form 135 will be favored. In fact evidence only for the dipolar and not for the closed form of diphenylacetolactone has been obtained (see below). In contrast strongly electron withdrawing groups should destabilize the carbonium ion center allowing a reasonably stable α -lactone to be isolated in the closed form 133. This possibility has yet to be tested.

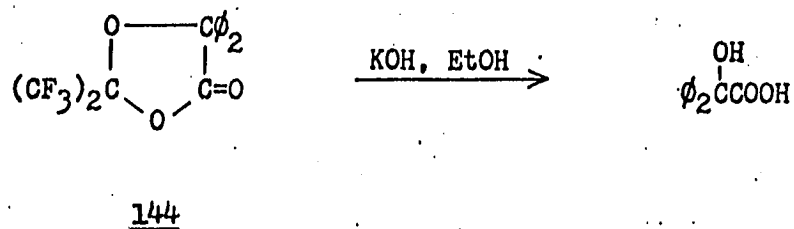


The elemental analysis for 144 is quite satisfactory.

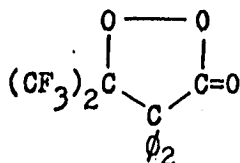
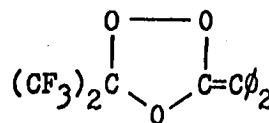
Anal. 144 Calc. for $\text{C}_{17}\text{H}_{10}\text{O}_3\text{F}_6$: C, 54.27%; H, 2.68%

Found: C, 54.49%; H, 2.66%

The ^{19}F nmr shows a strong singlet at 79ϕ with a half-height width of 9 Hz. The ^1H nmr shows only aromatic protons at 7-8 δ . The IR spectrum shows a carbonyl at 1830 cm^{-1} ; monosubstituted phenyl at 1480 cm^{-1} , 1440 cm^{-1} , 750 cm^{-1} , and 700 cm^{-1} ; and strong C-F at $1400\text{--}1100\text{ cm}^{-1}$. Basic hydrolysis affords benzilic acid, mp = $151\text{--}152^\circ\text{C}$ (reported mp = 151°C), neutralization equivalent = 228 (calc. 228).

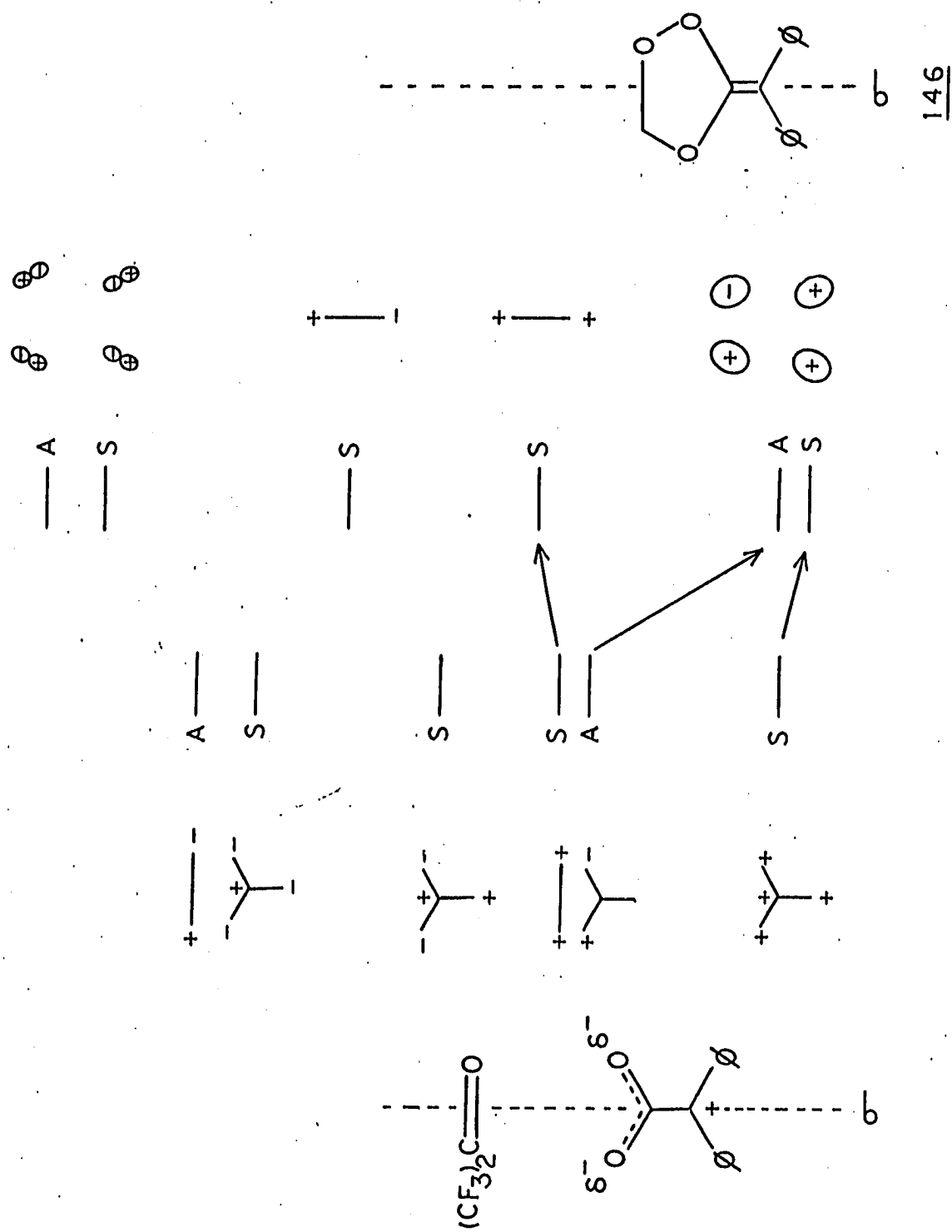


It should be noted that there are two other alternative 1:1 adduct structures between hexafluoroacetone and diphenylacetolactone 127. Both structures have severe drawbacks. In particular neither 145 nor 146 would be expected to have a strong parent peak in the mass spectrum, much less major $C_6H_5CO^+$ and ϕ_2CO^+ fragments. Structure 146 in no way accounts for the loss of CO_2 observed in the mass spectrum. The structures 145 and 146 with peroxy bonds are hardly consistent with the actual product which distills $b_{2-5} = 143^\circ C$ and which readily passes through a vpc column at $155^\circ C$. Structure 145 has the additional disadvantage of pairing the cationic center of the α -lactone with the positive end of the hexafluoroacetone carbonyl and the carboxylic anion portion of the α -lactone with the negative end of the hexafluoroacetone carbonyl.

145146

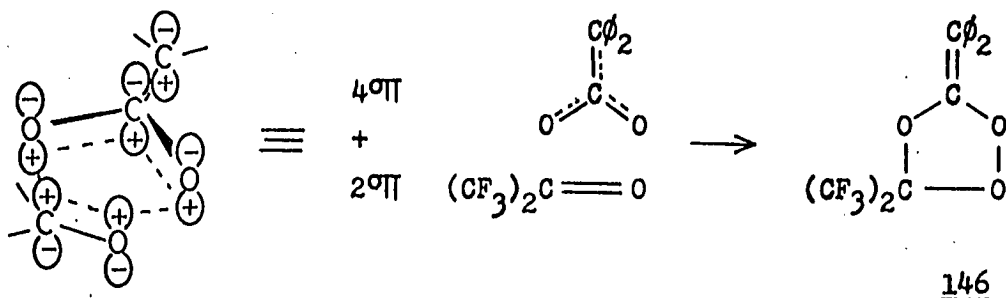
The interesting feature of the diphenylacetolactone cycloadduct to hexafluoroacetone is that a symmetry forbidden cycloadduct 144 is obtained even though a symmetry allowed cycloadduct 146 is possible. The orbital correlation diagram for 146 is shown on the next page (assuming no difference between carbon and oxygen for symmetry purposes).

Correlation Diagram for Hypothetical
Formation of 146

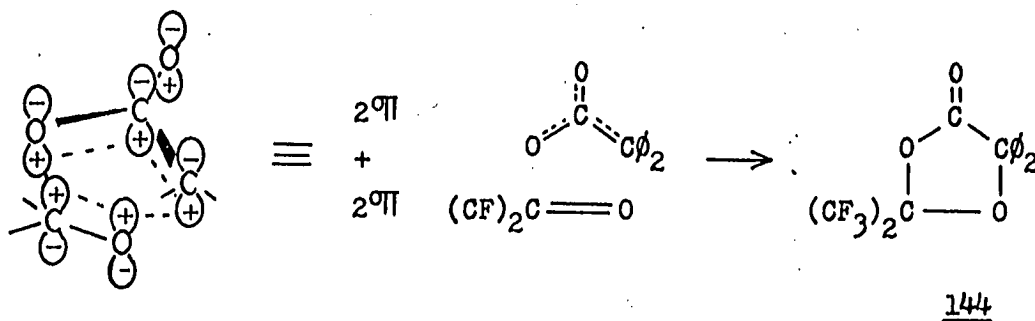


146

Alternatively one can consider the basis orbitals in the manner of Zimmerman.^{155a} Once again one predicts that 146 will be formed in a concerted manner since $6\sigma\pi$ electrons are involved in a Hückel manner with no sign inversions,



Adduct 144 that is obtained experimentally is not amenable to an orbital symmetry treatment because ψ_2 of the α -lactone (see p. 231) has a node at the $C\phi_2$ carbon atom which is one of the sites of new bond formation. However, based on our calculations it may be said that $O_3-C_1-C_2$ in the α -lactone 140 (see p. 231) contains $2\sigma\pi$ electrons and thus the concerted formation of 144 involves a disallowed $4\sigma\pi$ Hückel transition state with no sign inversions,^{155a}



155. a/ H. E. Zimmerman, *J. Am. Chem. Soc.*, **88**, 1564(1966). b/ K. Fukui and H. Fujimoto, *Bull. Chem. Soc. Jap.*, **40**, 2018(1967).

This use of Zimmerman's method assumes that the cyclic delocalized electrons connected by dotted lines in the two figures above are not significantly affected by the carbon or oxygen outside the five-membered ring. In defense of this assumption it should be noted that the very same approach accounts quite adequately for the cycloaddition behavior of analogous dipolar ions derived from cyclopropanones.¹³⁸ A consideration of frontier molecular orbitals^{155b} also leads to the identical conclusion that formation of 144 is symmetry forbidden and formation of 146 is symmetry allowed. If indeed 144 cannot be formed by a concerted mechanism, a two step dipolar process seems a reasonable alternative particularly since there are two phenyls to stabilize the carbonium ion center and two trifluoromethyl groups to stabilize the alkoxide group in the dipolar intermediate.

An explanation for the failure of diphenylacetolactone to cycloadd hexafluoroacetone in a symmetry allowed, concerted manner is suggested in a recent review by Huisgen.¹⁵⁶ Apparently dipolar cycloadditions generally take the path that maximizes the gain in σ bond energy. In fact if the overall gain in σ bond energy is sufficiently small, no reaction occurs at all. A prime example is the observation that ozone, a $4\sigma\pi$ 1,3-dipolar reagent, readily attacks C=C bonds but not C=O bonds. In the case of C=C bond attack two 100 kcal/mole C-O bonds are formed whereas in the case of C=O bond attack only one such C-O bond is formed along with a very weak O-O bond. Similarly in the observed cycloadduct 144 one C-O and one C-C bond are formed in the process of

156. R. Huisgen, Angew. Chem. Internat. Ed. Eng., 2, 633(1963).

addition whereas in 146 which is not observed one C-O and one very weak O-O bond would be formed.

If one wishes to observe $4\sigma\pi$ cycloaddition behavior on the part of diphenylacetolactone, compounds such as tetracyanoethylene and hexafluoro-2-butyne would be more suitable. In both cases $4\sigma\pi$ cycloaddition to diphenylacetolactone would result in the formation of two C-O bonds. The strongly electron withdrawing groups would favor attack by the electron rich carboxylate anion portion of the α -lactone while simultaneously discouraging attack by ozone. Such experiments have not yet been tried.

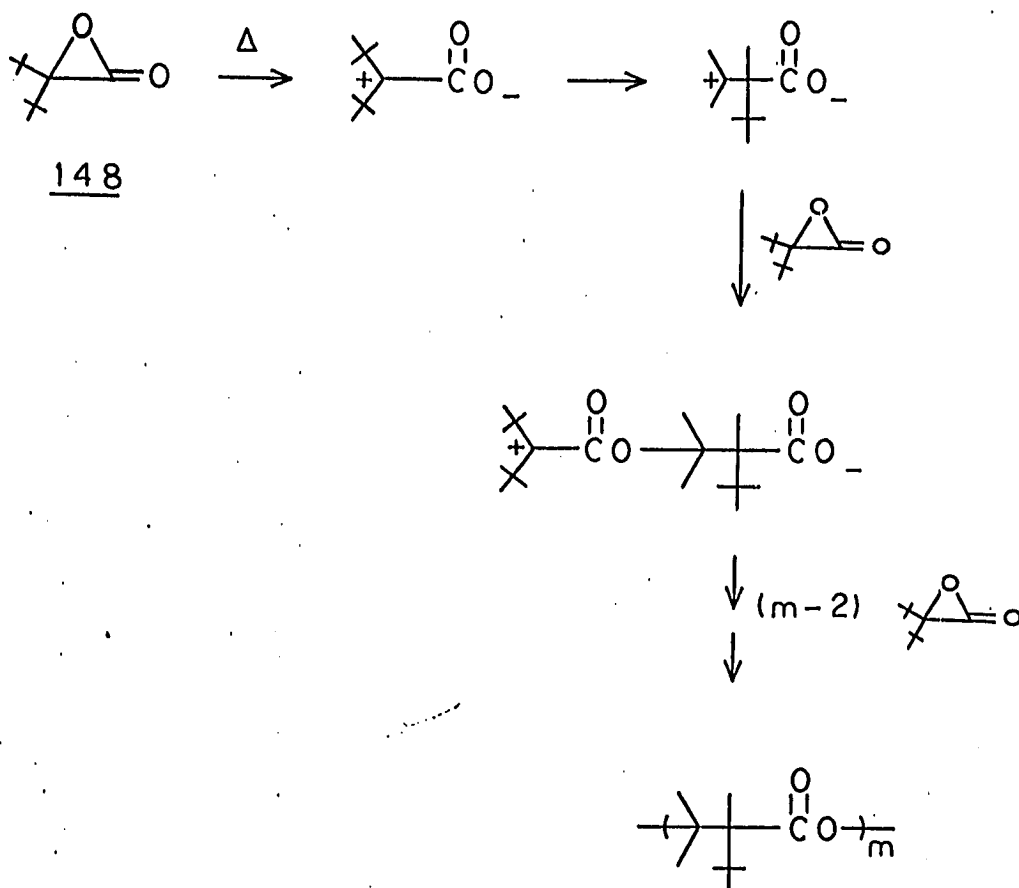
B. From the addition of diphenylcarbene to carbon dioxide

The addition of carbenes or such carbene precursors as diazomethanes to cumulated double bonds has proved a convenient source of cyclopropyl compounds with a single sp^2 carbon in the ring: for example, the reaction of diazomethane with ketene to give cyclopropanone,^{157a} the addition of dichlorocarbene to allene to give 2,2-dichloro-1-methylenecyclopropane,¹²⁸ and the addition of bis(trifluoromethyl)diazomethane to bis(trifluoromethyl)thio ketene to give 2,2-bis(trifluoromethyl)-3-bis(trifluoromethyl)-methylenethiirane.^{157b} Not all such additions have proved synthetically useful such as that of carbenes to isocyanates to give α -lactams.¹⁵¹

Sunlamp irradiation of a diphenyldiazomethane solution in a clear Pyrex dewar in a $CFCl_3$ -dry ice slurry produces polyester 128 identified by IR comparison to a genuine sample. This polyester is then treated with methanol in refluxing benzene giving 143 identified by IR and

157. a/ N. J. Turro and W. B. Hammond, *J. Am. Chem. Soc.*, **88**, 3672(1966).
 b/ W. J. Middleton, *J. Org. Chem.*, **34**, 3201(1969).

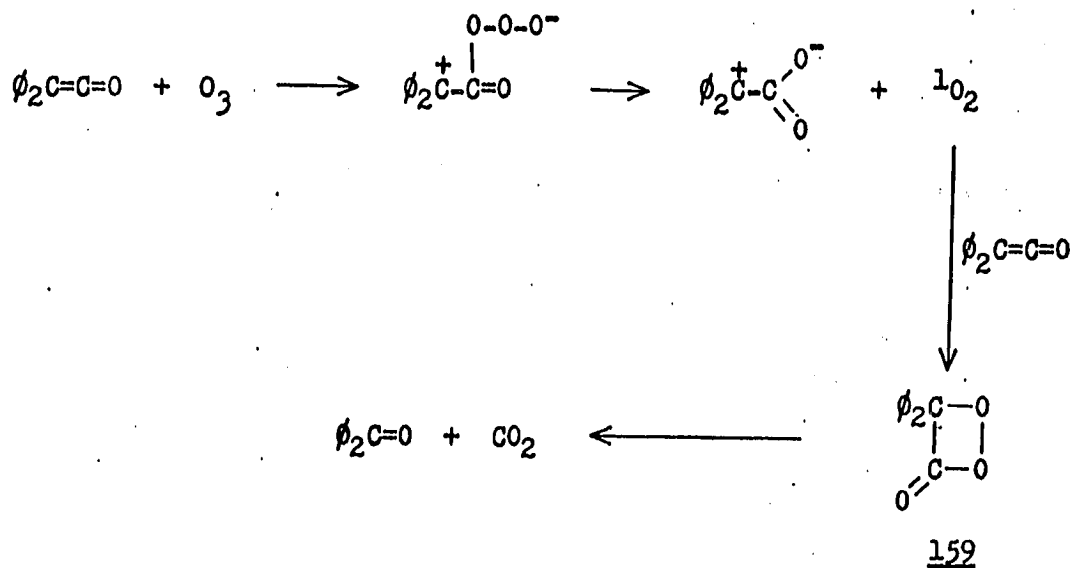
This incorporation of unrearranged units by basic carboxyl attack finds its analogy in the basic attack of ammonia on lactone 148 and in the solvolysis of α -halocarboxylate ions. On the other hand one may suggest that attack by the carbonium ion end of the rearranged zwitterion 158 leads to successive incorporation of rearranged units into the polyester 153.



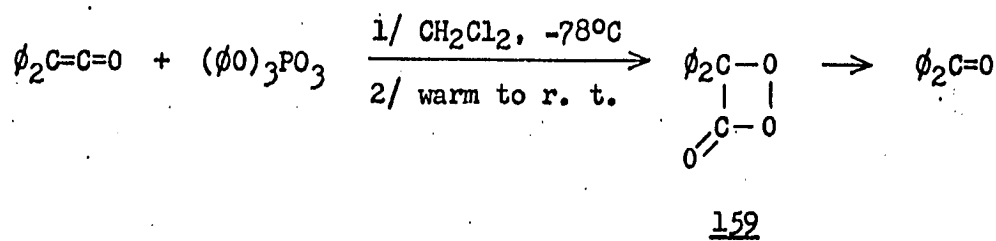
In conclusion it is interesting to note that in one regard di-*t*-butylacetolactone and diphenylacetolactone are quite divergent in their behavior. Ozonization of di-*t*-butylketene in CFCl_3 at -78°C

B. Trapping of singlet oxygen by ketene

It is quite possible that the singlet oxygen presumably formed during ozonization of the ketene is then trapped by unreacted ketene to give dioxetanone 159 that in turn decomposes to carbon dioxide and ketone; for example,

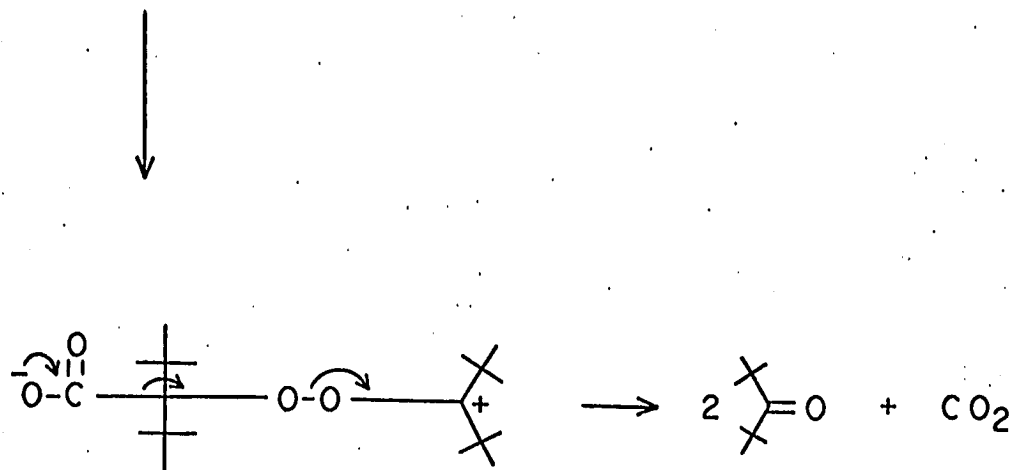


Indeed, Bollyky reports that triphenylphosphite ozonide gives a 40% yield of benzophenone with diphenylketene,¹⁶³



While Bollyky assumes that 159 is formed by the addition of singlet

163. L. J. Bollyky, J. Am. Chem. Soc., 92, 3230(1970).



Bailey has already shown that epoxidation of olefins by ozone increasingly occurs to the exclusion of ozonolysis with increasingly bulky olefinic groups.^{152a} This same reasoning applied to ketene ozonization would suggest that more ketone and less polyester will be formed with diphenylketene than with di-*t*-butylketene. Since this is in fact observed, the hydroperoxide scheme is felt to rationalize the formation of ketones most successfully.

recrystallizations from benzene-petroleum ether gave 0.88 g (67%) of fine white crystals of benzoic acid, mp = 151-152°C (reported 152°C).

Exactly 0.1374 g of this product was dissolved in a mixture of 10 ml of methanol with 5 ml of water. Titration with 6.095 ml of 0.09904 N NaOH gave an endpoint with phenolphthalein from which a neutralization equivalent of 227.6 (calc. 228 for benzoic acid) was calculated.

Failure of Diphenylketene to React with Hexafluoroacetone. In a vacuum trap being swept out by nitrogen, 4.3 g of diphenylketene in 20 ml of ethyl acetate were stirred magnetically. The reaction mixture was cooled in dry ice-methanol and then 20-30 ml of hexafluoroacetone were distilled in. After 1 hr of vigorous stirring a heavy yellow slush had formed that impeded continuance of magnetic stirring. The hexafluoroacetone was allowed to distill off as the reaction mixture warmed to room temperature. After the system was blown out with nitrogen, the yellow solution was transferred to a rotary evaporator. According to its IR spectrum, the resulting residue was simply dirty diphenylketene which had undergone no major changes.

Ozonization of Di-t-butylketene in CFCl_3 . Isolation of Polyester 153, Di-t-butyl Ketone, and Trimethyl-t-butylethylene 155. With cooling in a dry ice-methanol slush bath, 2.0 g of di-t-butylketene (^1H nmr, singlet 1.2 δ ; IR C=O 4.8 μ),¹⁶⁶ were ozonized in 50 ml of CFCl_3 until the solution was blue (15 minutes). Excess ozone was

166. M. S. Newman, A. Arkell, and T. Fukunaga, *J. Am. Chem. Soc.*, **82**, 2498 (1960).

blown out with nitrogen until the solution was entirely colorless. This solution of di-t-butylacetolactone appeared stable for several hours and was suitable for studying the reactions of di-t-butylacetolactone. If the nitrogen flow was allowed to continue as the reaction vessel was removed from its cooling bath, initial clouding occurred at -26°C and by -10°C the solution was quite opaque with a fine white precipitate. After standing for 15 to 20 minutes, the reaction mixture was vacuum filtered several times through the same filter until the filtrate came through entirely clear. The precipitate was washed with CFCl_3 . The air dried precipitate weighed 2.02 g (91% of polyester 153) and readily crushed to a fine white powder.

The filtrate was concentrated to a small volume by distillation of the CFCl_3 at atmospheric pressure. One obtained two major product peaks on a 10M X $\frac{1}{4}$ " , 20% Carbowax 20M, 30/60W AW DMCS column at 110°C . There was collected 12 mg (0.7%) of material with the retention time (13 minutes) of 155 and 23 mg (1.2%) of material with the retention time (26 minutes) of di-t-butyl ketone. Assignment of the structures of di-t-butyl ketone and 155 were confirmed by IR and nmr comparison to genuine samples.¹⁶⁷

Reaction of Ammonia with Di-t-butylacetolactone in CFCl_3 .

Preparation of Di-t-butylglycine 151. Lactone 148 was prepared in 25 ml of CFCl_3 cooled in a dry ice-methanol bath starting with 1.0 g of di-t-butylketone. Roughly 2 ml of anhydrous ammonia were condensed

167. Di-t-butyl ketone sample prepared by the method of P. D. Bartlett - and A. Schneider, J. Am. Chem. Soc., 67, 141(1945).

in a cold finger trap cooled in a dry ice-methanol bath. The ammonia trap was removed from the cooling bath and its contents blown into the lactone solution with a stream of nitrogen. The reaction mixture took on a sufficiently thick and gelatinous consistency that an additional 50 ml of CFCl_3 precooled to -78°C were added. Once all of the ammonia had been distilled in, the reaction vessel was capped and allowed to stand in its cooling bath for 3 hr. The reaction mixture was allowed to warm to room temperature and then to stand for an additional 4 hr. Vacuum filtration and overnight drying gave 1.2 g (100%) of amino acid 151. Recrystallization was carried out for analytical purposes although the IR spectra was unaffected by recrystallization. One gram of 151 was dissolved in 180 ml of refluxing water. The resulting solution was refluxed down to roughly 80 ml. Cooling the solution produced only a small quantity of crystals and hence more solvent was pulled off on a rotary evaporator until a sizable quantity had formed. Filtration and air drying gave 0.31 g of 151 with a satisfactory elemental analysis. Amino acid 151 sublimed rapidly in the $250\text{-}300^\circ\text{C}$ range without apparent melting or decomposition. The mass spectrum showed no parent peak but major peaks at mass 142 (loss of $-\text{COOH}$), mass 130 (loss of t-butyl), and a base peak at mass 57 (t-butyl).

Attempted Trapping of Lactone 148 with Hexafluoroacetone.

Preparation of Trimethyl-t-butylethylene 155 and of 1-t-Butyl-1,2,2-trimethyl- β -propiolactone 157. Lactone 148 was prepared by ozonization.

of 3 g of di-*t*-butylketene in 75 ml of CFCl_3 cooled in a dry ice-methanol bath. Roughly 30 ml of hexafluoroacetone was distilled in. The mixture was stirred under a slow flow of nitrogen for 1 hr. The nitrogen flow was stopped and the reaction vessel removed from its cooling bath. After 40 min the nitrogen flow was restarted and continued until the total volume of the reaction mixture had been reduced to roughly 40 ml. The residue was further concentrated on a rotary evaporator and then distilled. There was obtained 0.9 g of colorless liquid $b_{45} = 44^\circ\text{C}$. Injection of 70 mg of this fraction on a 10M X $\frac{1}{4}$ ", 20% Carbowax 20M, 30/60W AW DMCS column at 95°C gave 56 mg of material with the retention time (17 minutes) of 155. The structure of 155 was confirmed by IR and nmr. Presumably $900/75 \times 56 = 720$ mg of 155 (29%) could be collected if the whole sample were collected off the vpc.

Further distillation of the reaction mixture gave 1.35 g of 157 (21%) $b_8 = 84^\circ\text{C}$. Collection of this material off a teflon 2.5' X $\frac{1}{4}$ ", 20% Carbowax 20M, 30/60W AW DMCS column at 105°C with an injector temperature of 120°C and a detector temperature of 117°C gave essentially a single peak with a 35 minute retention time. The nmr of this peak after collection off the vpc, however, showed some impurities which were not present before vpc passage. Reinjection of the material collected off the vpc now showed a volatile component with a one minute retention time that was not present in the original $b_8 = 84^\circ\text{C}$ sample. This decomposition was accentuated by raising the injector temperature to 310°C . Now if the $b_8 = 84^\circ\text{C}$ fraction was injected on the vpc,

there was an immediate strong peak, a peak with a one minute retention time, and practically no 157 with a 35 minute retention time. Injection of 81 mg of 157, $b_8 = 84^\circ\text{C}$, under these conditions allowed collection of 22 mg (71%) of 155 with a one minute retention time (identified by IR, nmr, and vpc retention time). On a 10M X $\frac{1}{4}$ ", 20% Carbowax 20M, 30/60W AW DMCS column at 27°C with an injector temperature of 310°C and a detector temperature of 120°C , the extremely volatile decomposition product from 157 now had a six minute retention time. Running this fraction off the vpc into an IR gas cell gave an IR spectrum identical to that of carbon dioxide. Thus 157 decomposed to two and only two fragments, carbon dioxide and 155. Since this decomposition occurred so readily none of the vpc samples were sent for elemental analysis but rather the fraction $b_8 = 84^\circ\text{C}$.

Addition of Ether to a CFCl_3 Solution of Lactone 148. Preparation of Trimethyl-t-butylethylene 155 and 1-t-Butyl-1,2-dimethyl-3-butenic Acid 156. Lactone 148 was prepared by ozonolysis of 0.66 g of di-t-butylketene in 10 ml of CFCl_3 cooled to -90 to -100°C with a hexane-nitrogen slush. The solution was continually swept out with nitrogen gas. Fifty ml of precooled ether was added and then the reaction mixture was removed from the cooling bath. The reaction mixture was allowed to warm above 0°C and then was reduced to an oil with a rotary evaporator. The oil was diluted with sufficient ether to allow easy injection on a 10M X $\frac{1}{4}$ ", 20% Carbowax 20M, 30/60W AW DMCS column at 170°C . There was collected a highly volatile fraction which was put through again at lower temperature, 45 mg of 156 (7%)

with a 55 minute retention time, and 46 mg of an unidentified material with a 196 minute retention time. This unidentified material had only a sharp singlet at 1.1 τ in the nmr. The IR showed -COOH at 2300-3400 cm^{-1} , and a very sharp rather strong absorption at 3550 cm^{-1} which would normally have suggested a free hydroxyl group. From the highly volatile fraction there was isolated 124 mg (27%) of 155 on reinjection on a 4M X $\frac{1}{4}$ " , 25% TCEP, 60/80P column.

Degradation of Polyester 153:

A. Thermolysis to Trimethyl-t-butylethylene 155 and to 1-t-Butyl-1,2-dimethyl-3-butenic Acid 156. Heat was applied to 0.5 g of polyester 153 in a 100 ml flask connected to one arm of an evacuated bulb-to-bulb apparatus. When the supporting heating mantle reached roughly 80°C, the material began to distill over rapidly. Within 10-15 minutes the mantle had reached 180°C and was removed. A heat gun was used to complete liquid transfer totaling 0.3 g (85%) of crude 155. Vpc purification of 155 gave 0.19 g (54%) of pure 155 used hereafter as the IR and nmr standard for this compound in other comparisons. When the solids that had remained behind on the walls of the bulb-to-bulb apparatus were put through the vpc, there was obtained 7 mg (1.4%) of 156 identified by IR and nmr.

This thermal decomposition of 128 occurred even at room temperature. If 1.0 g of polyester 153 was sealed in a flask for a month and the contents bulb-to-bulb distilled without any heating, there was obtained 130 mg of crude 155 which with purification on the vpc gave 56 mg of

Attempted Reaction of Di-t-butylketene with Singlet Oxygen. Reactions were carried out in an nmr tube as it was immersed in a clear Pyrex dewar containing dry ice-acetone. Singlet oxygen was generated by rose bengal photosensitization of oxygen at 562 m μ . Apparatus and conditions were identical to those found to lead to the complete reaction of 15 mg (0.13 mmole) of 1,2-diethoxyethylene in deuterioacetone in 80 min.

Roughly 21 mg (0.15 mmole) of di-t-butylketene in 0.3 ml of acetone, 0.1 ml CH₂Cl₂, and a trace of TMS were irradiated in the presence of rose bengal for 3 hr as oxygen was bubbled through. The nmr of the reaction mixture was identical to that before irradiation. The contents of the tube were evaporated to a residue. The IR of this residue was nearly identical to that of di-t-butylketene. Even when the band for C=C=O was run off scale in the IR, only the slightest blip was apparent at the position of C=O for di-t-butylketone. Vpc analysis could not be profitably applied here since di-t-butylketene gave a number of peaks on vapor phase chromatography, one peak of which had the retention time of di-t-butyl ketone. It should also be mentioned that inasmuch as di-t-butylketene and di-t-butyl ketone had the same chemical shift (1.2 δ), nmr analysis was of only peripheral value in following the course of reaction.

Roughly 21 mg (0.15 mmole) of di-t-butylketene in 0.3 ml of deuterioacetone and 25 μ l of acetone in the presence of rose bengal and oxygen was irradiated for 27 hr. The nmr after reaction indicated that the di-t-butylketene and/or di-t-butyl ketone peaks at 1.2 δ had decreased

relative to acetone with the formation of a number of smaller peaks. Evaporation to a residue gave a complex IR spectrum with at least five absorptions in the C=O region. Much of the di-t-butylketene still remained, however, as deduced from the C=C=O absorption at 2100 cm^{-1} . From the IR alone one was unable to pass judgement on the presence or absence of di-t-butyl ketone.

Reaction of Di-t-butylketene with Triphenylphosphite Ozonide.

Dropwise addition of 3.15 g of triphenylphosphite to 75 ml of dry ice-methanol cooled CFCl_3 blue with ozone gave 10.2 mmole of triphenylphosphite ozonide. Excess ozone was blown out with nitrogen and then 102 mg of di-t-butylketene (0.66 mmole) were washed in with a small volume of CFCl_3 . The reaction mixture was removed from the cooling bath. Evolution of oxygen became vigorous at 0°C . Vigorous bubbling continued for about 10 min and then dropped off over the next 50 min. The reaction mixture was reduced to roughly 15 ml and then was bulb-to-bulb distilled overnight at 1 mm with stirring and mild heating. The bulb-to-bulb distillate was reduced in volume to 10-20 μl on a rotary evaporator. An IR of one portion of this crude residue indicated the complete absence of starting ketene and suggested the presence of di-t-butyl ketone. Injection of the remaining residue on a 10M X $\frac{1}{4}$ " 20% Carbowax 20M, 30/60W AW DMCS column at 110°C allowed collection of 3 mg (3%) of material with the retention time of di-t-butyl ketone. This material had the correct nmr for di-t-butyl ketone and was the only product investigated.

Reaction of t-Butyl Hydroperoxide with Di-t-butylacetolactone 148.

Formation of Di-t-butyl Ketone. Di-t-butylacetolactone was prepared from 0.32 g of di-t-butylketene in 25 ml of CFCl_3 at -78°C . Roughly 0.6 g of t-butyl hydroperoxide in 5-6 ml of CFCl_3 was added dropwise. The reaction mixture was allowed to warm to room temperature under a flow of nitrogen. The reaction mixture was evaporated to a heavy oil with a rotary evaporator. At this point neither the IR spectrum nor the vpc of this residue suggested the presence of significant quantities of di-t-butyl ketone. After 3 days the absorption of the $\text{C}=\text{O}$ group of di-t-butyl ketone was apparent in the IR spectrum. No additional development of the $\text{C}=\text{O}$ band was noted after the reaction mixture had stood an additional two days. Vpc collection off a $10\text{M} \times \frac{1}{4}"$, 20% Carbowax 20M, 30/60W AW DMCS column at 110°C gave 29.1 mg of di-t-butyl ketone (10.5%) identified by IR and nmr comparison to a genuine sample. There was also collected 4 mg of material with the retention time of 155 which the nmr spectrum suggested was impure.

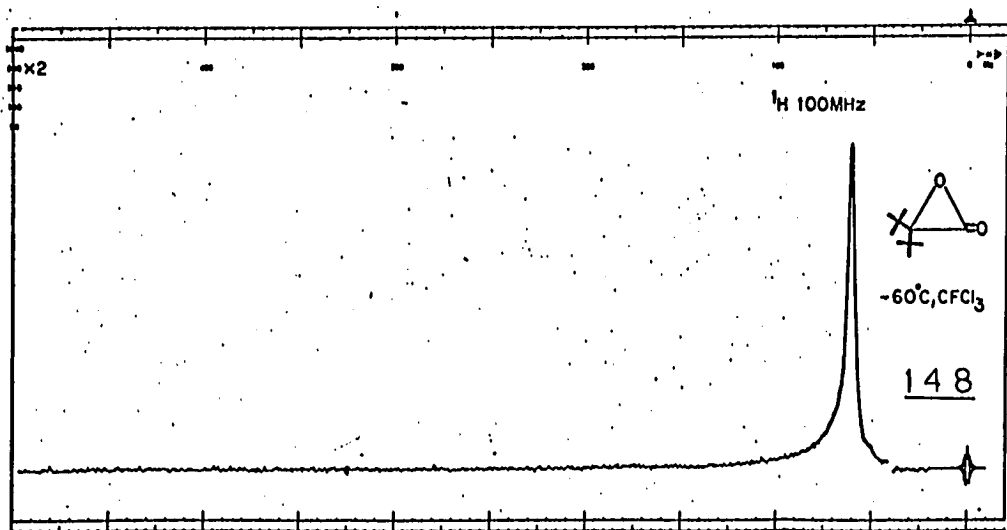
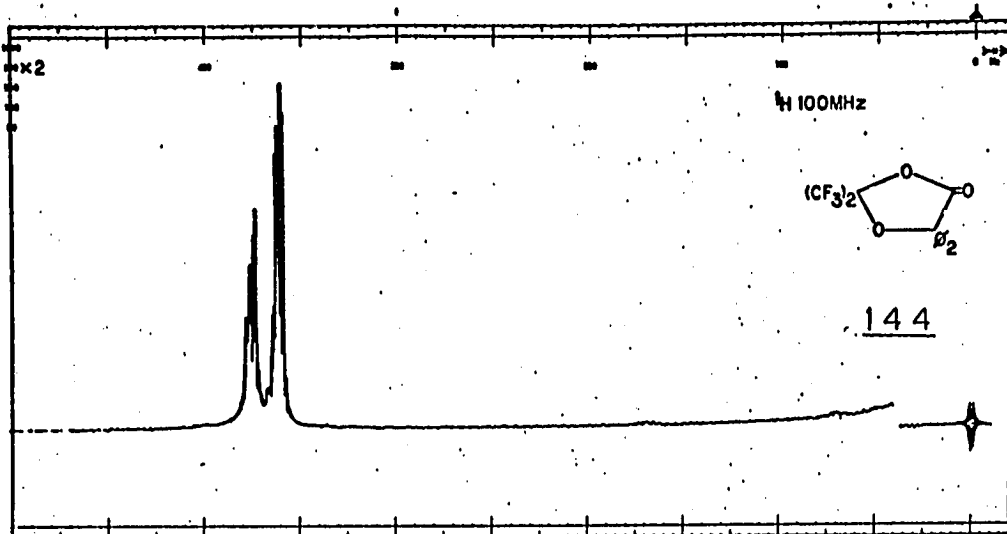
Benzophenone from the Ozonization of Diphenylketene. With cooling in a dry ice-methanol bath 2.0 g of diphenylketene stabilized with hydroquinone was ozonized in 60 ml of CFCl_3 . Within 10 min the solution had taken on a blue tinge and excess ozone was blown out with nitrogen. The nitrogen flow was continued as the solution warmed towards room temperature. The white precipitate was vacuum filtered three times through the same filter until the filtrate ran clear. There was obtained 1.45 g of benzoic acid polyester 128 (67%) on air drying.

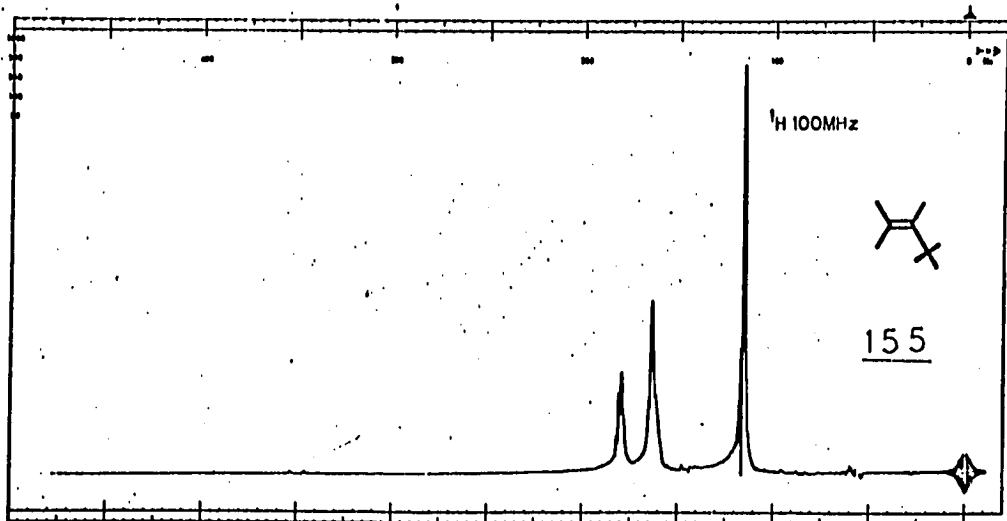
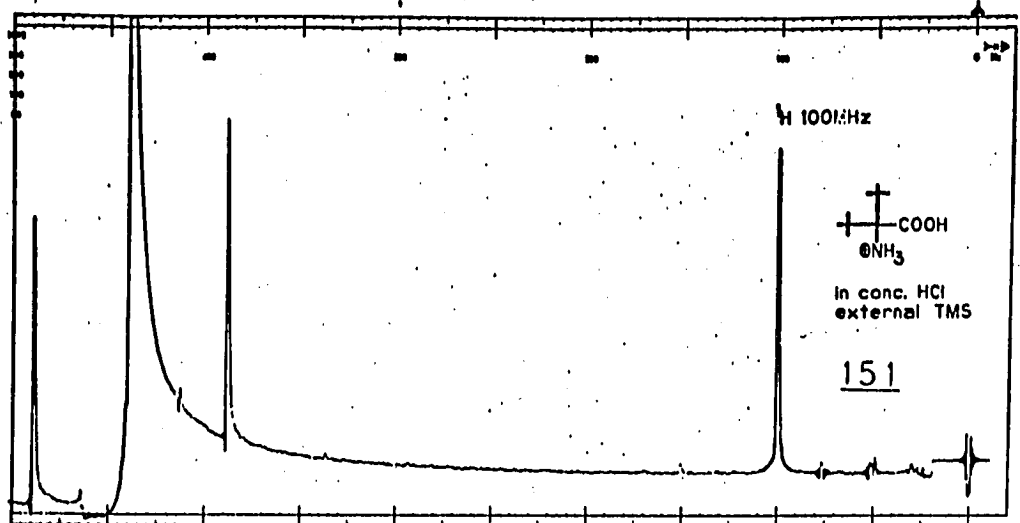
The filtrate was concentrated to a yellow resin that was taken up in benzene and put through 10 g of Woelm silica gel. Injection of the resulting colorless oil on a 3M X $\frac{1}{4}$ ", 20% Carbowax 20M, 30/60W AW DMCS column at 215°C gave a colorless oil with the 25 min retention time of benzophenone. The 170 mg of oil collected (9.1% crude yield) had an IR spectrum very similar to that of a genuine sample of benzophenone. Crystallization from methanol gave 101 mg (5.4%) of benzophenone with the correct IR, nmr, and mp = 47-49°C (reported mp = 49°C α form and mp = 45-48°C β form).

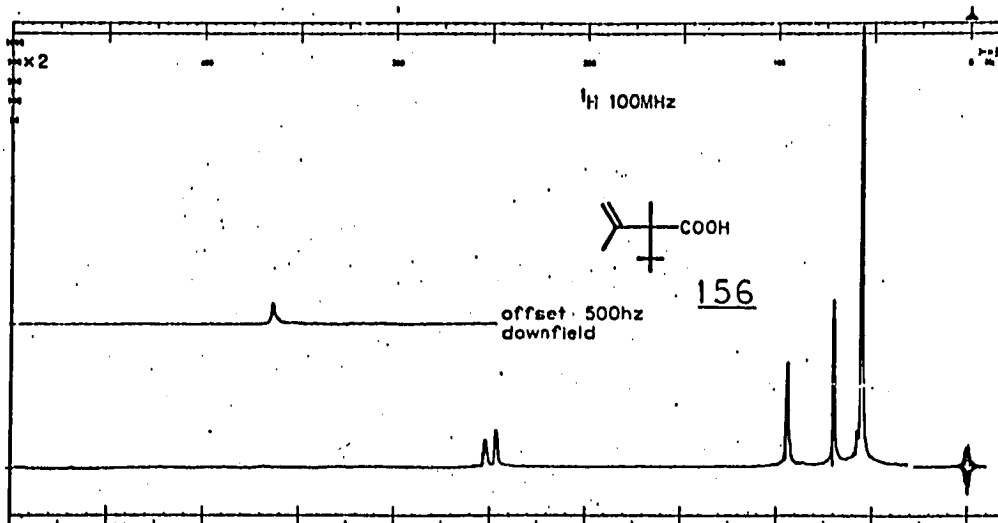
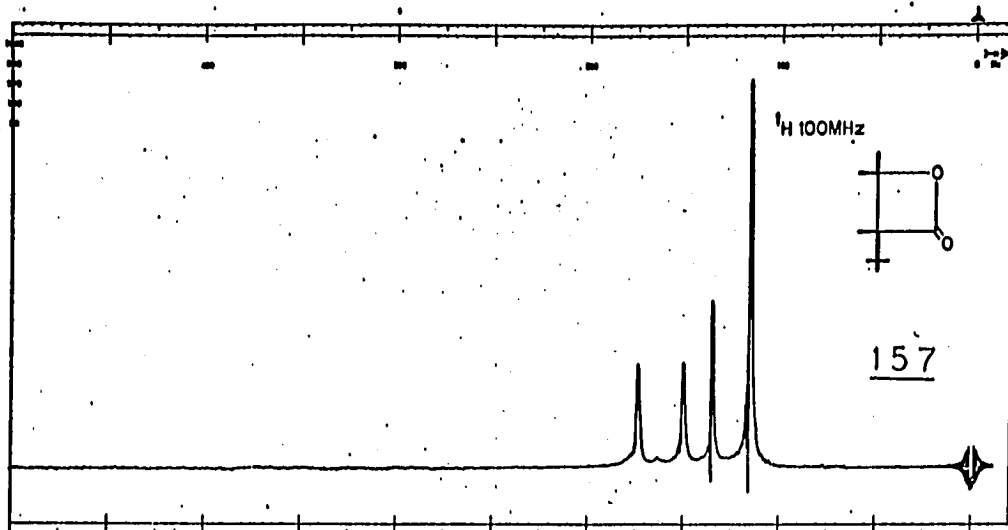
Summary of Nmr Chemical Shifts

Compound (solvent)	Chemical Shift			
	t-butyl protons	methyl protons	vinyl protons	acid protons
di-t-butyl ketone (CCl ₄)	1.2 δ s			
di-t-butylketene (CH ₃ COCH ₃ , CH ₂ Cl ₂)	1.2 δ s			
di-t-butylacetolactone (CFC1 ₃)	1.2 δ s			
<u>151</u> (conc. HCl)	2.0 δ s			
<u>155</u> (CCl ₄)	1.2 δ s	1.6 δ m 1.6 δ m 1.8 δ q		
<u>157</u> (CCl ₄)	1.2 δ s	1.4 δ s 1.5 δ s 1.7 δ s		
<u>156</u> (CCl ₄)	1.2 δ s	1.4 δ s 1.9 δ s	4.94 δ s 5.04 δ m	12.3 δ s

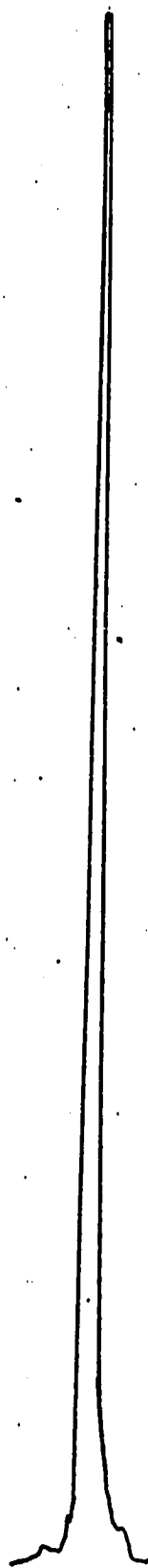
s = singlet, q = quartet, m = multiplet



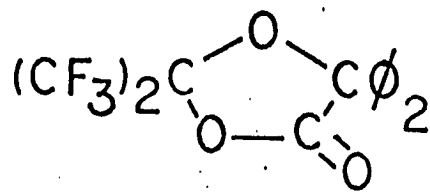




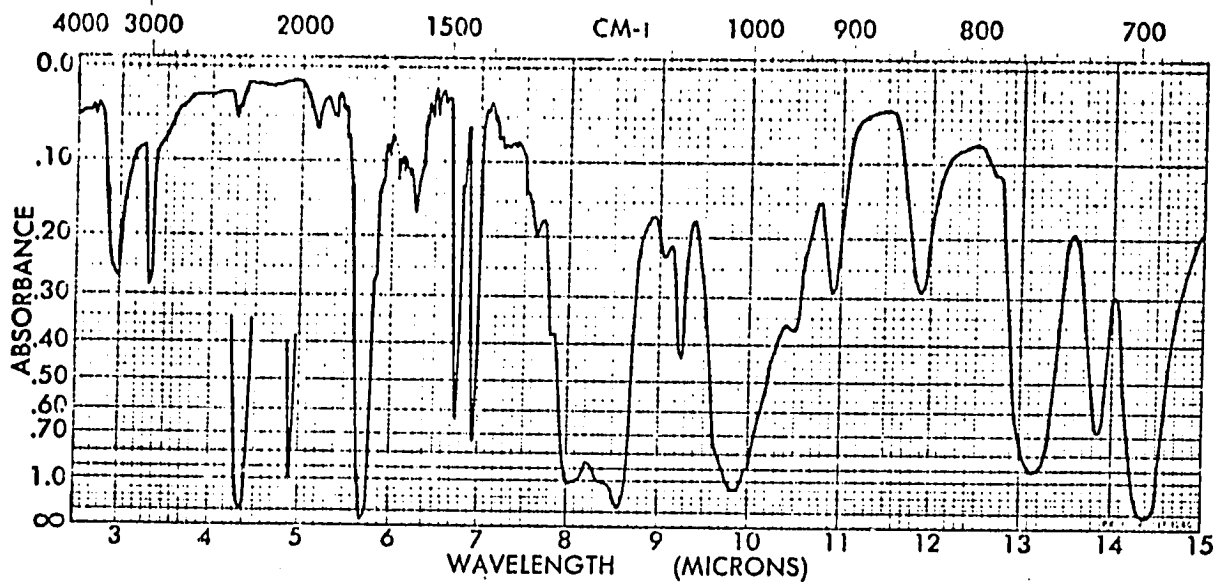
^{19}F NMR 94.1Mhz



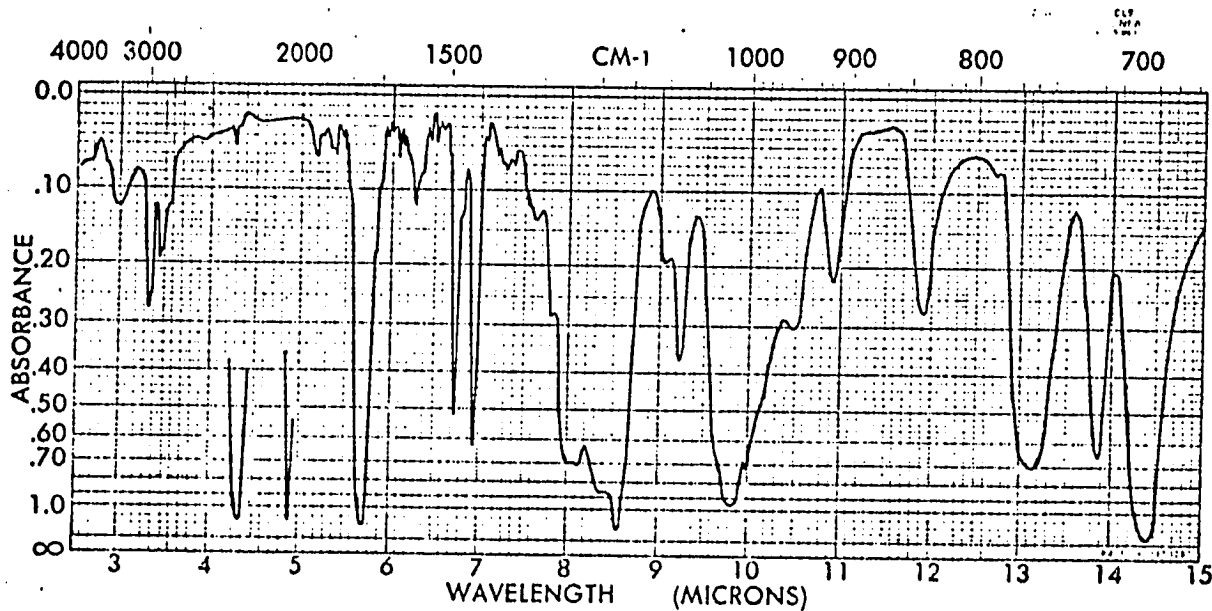
79.0



144

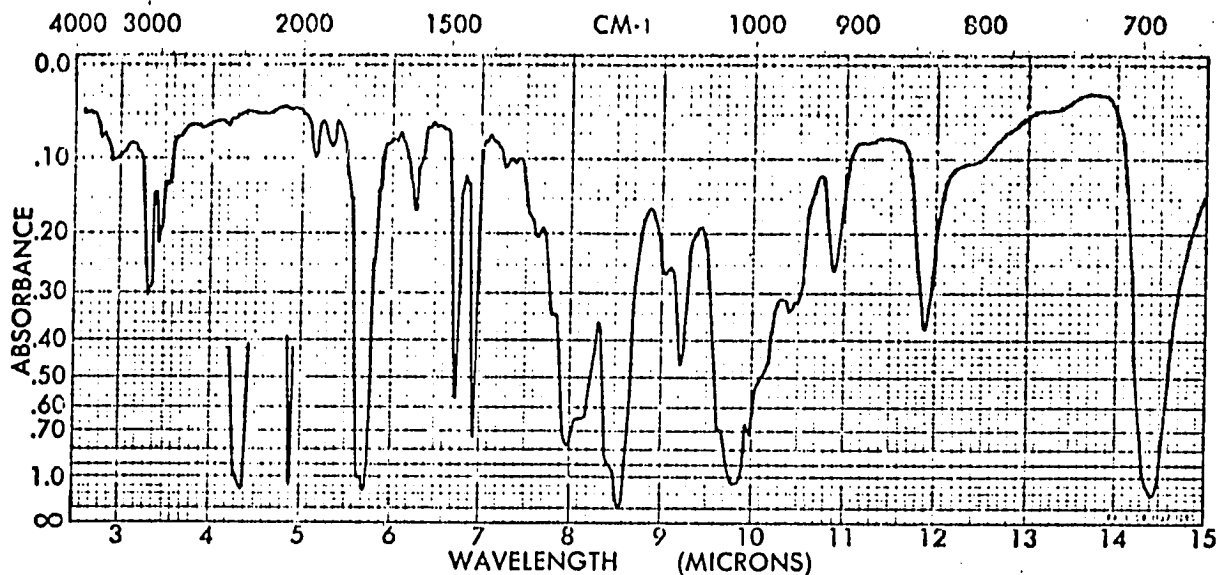


SPECTRUM NO.	ORIGIN	LEGEND	REMARKS	SAMPLE	SPECTRUM NO.
128	$\phi_2C=C=O + O_3$	1. _____	6.24 μ Std. vs.		
$+C\phi_2\overset{O}{\parallel}C\phi_n$	PURITY _____	2. _____	5.7 μ Sample		
	PHASE KBr Pellet	DATE _____			
	THICKNESS _____	OPERATOR _____			



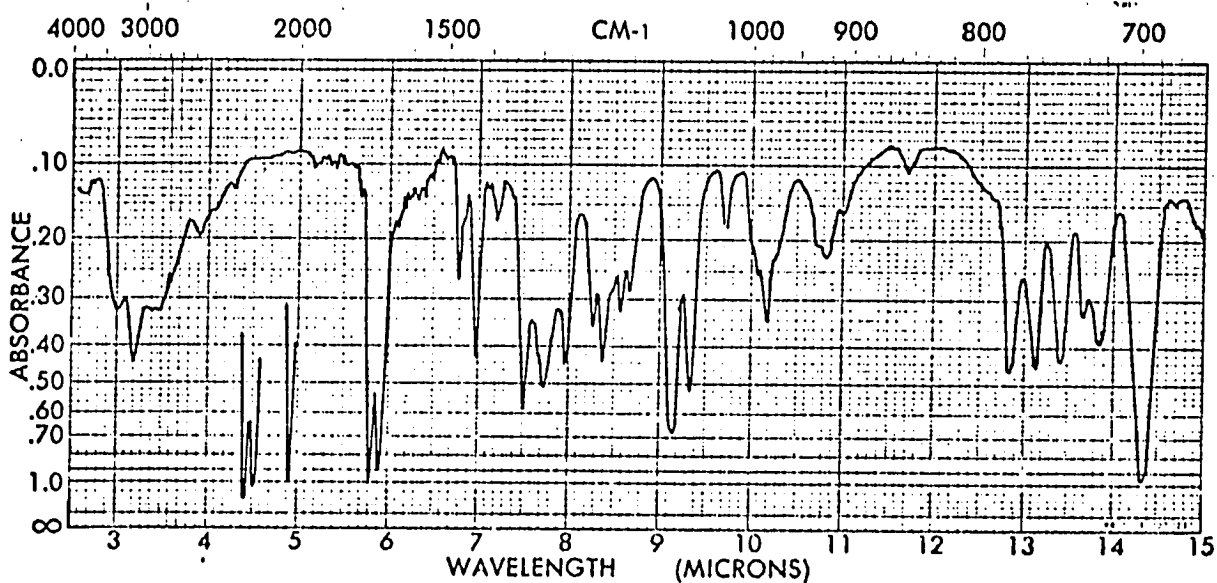
SPECTRUM NO.	ORIGIN	LEGEND	REMARKS	SAMPLE	SPECTRUM NO.
128	$\phi_2CN_2 + CO_2$	1. _____	6.24 μ Std. vs.		
$+C\phi_2\overset{O}{\parallel}C\phi_n$	PURITY _____	2. _____	5.7 μ Sample		
	PHASE KBr Pellet	DATE _____			
	THICKNESS _____	OPERATOR _____			

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SPECTRUM NO.	ORIGIN	LEGEND	REMARKS
128	$\phi_2\text{CN}_2 + \text{CO}_2$	1.	6.24 μ Std. vs.
$+\text{C}\overset{\text{O}}{\parallel}\text{C}\text{O}+_n$	PURITY	2.	5.7 μ Sample
	PHASE in CHCl_3	DATE	
	THICKNESS	OPERATOR	

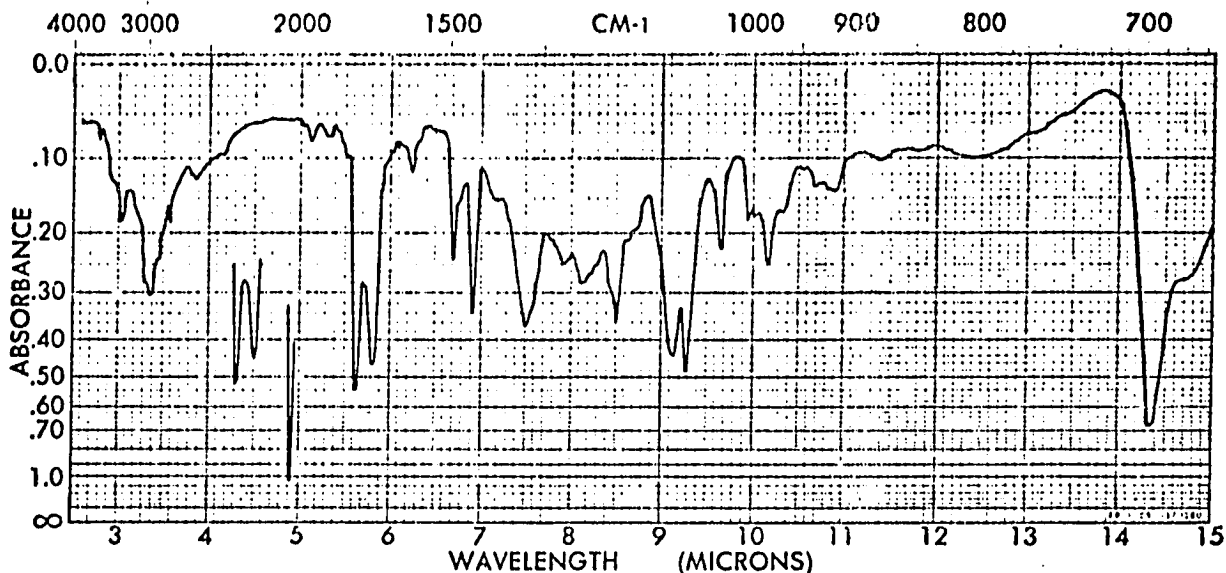
SPECTRUM NO. SAMPLE



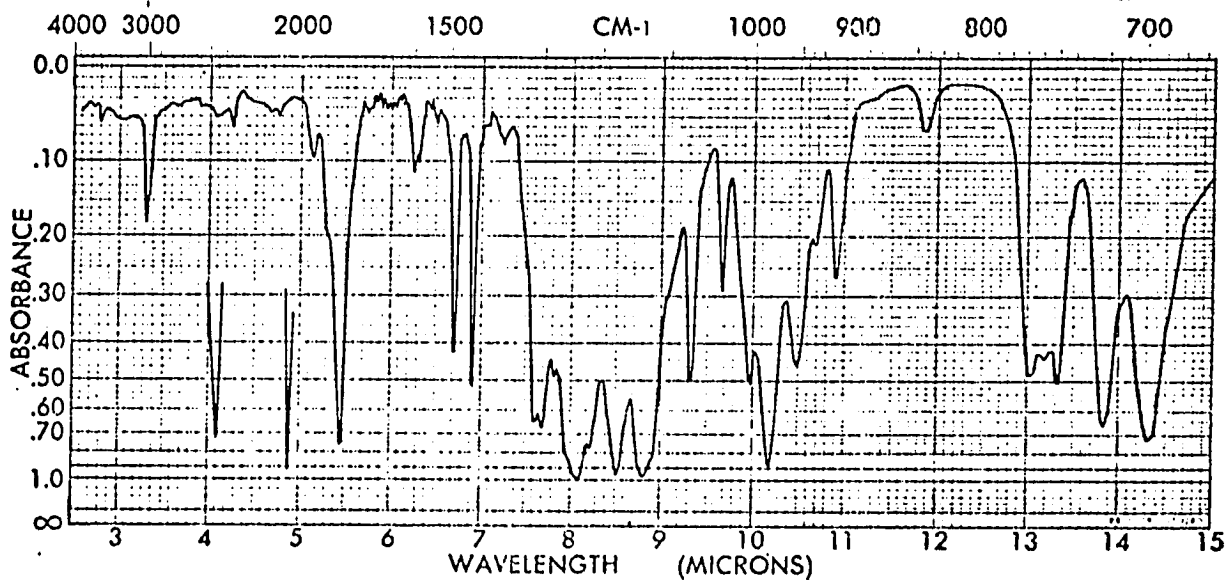
SPECTRUM NO.	ORIGIN	LEGEND	REMARKS
143		1.	6.24 μ Std. vs.
OMe $\phi_2\text{C}\overset{\text{O}}{\parallel}\text{COOH}$	PURITY	2.	5.8 μ Sample
	PHASE KBr Pellet	DATE	
	THICKNESS	OPERATOR	

SPECTRUM NO. SAMPLE

RECORDING CHART
DATE: _____
TIME: _____
NO. _____

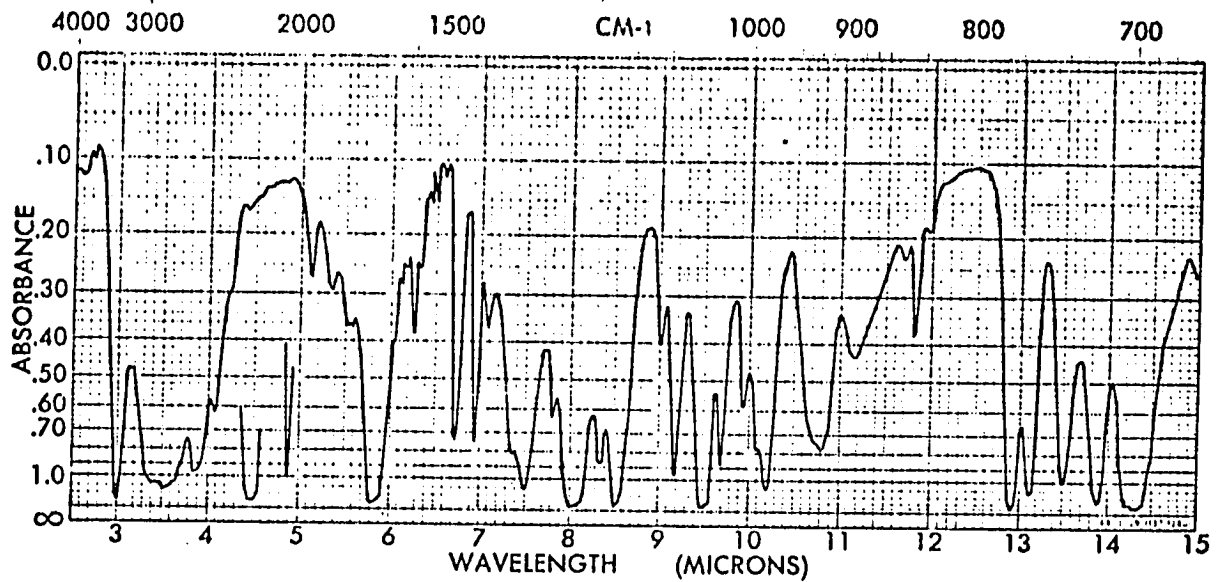


SPECTRUM NO.	ORIGIN	LEGEND	REMARKS	SAMPLE NO.
SAMPLE <u>143</u>		1.	6.24µ Std. vs.	
<chem>COc1ccc(cc1)C(=O)O</chem>	PURITY	2.	5.6µ Sample	
	PHASE in <u>CHCl₃</u>	DATE		
	THICKNESS	OPERATOR		



SPECTRUM NO.	ORIGIN	LEGEND	REMARKS	SAMPLE NO.
SAMPLE <u>144</u>		1.	6.24µ Std. vs.	
<chem>COC1OC(C(F)(F)F)C(=O)O1</chem>	PURITY	2.	5.5µ Sample	
	PHASE <u>Neat</u>	DATE		
	THICKNESS	OPERATOR		

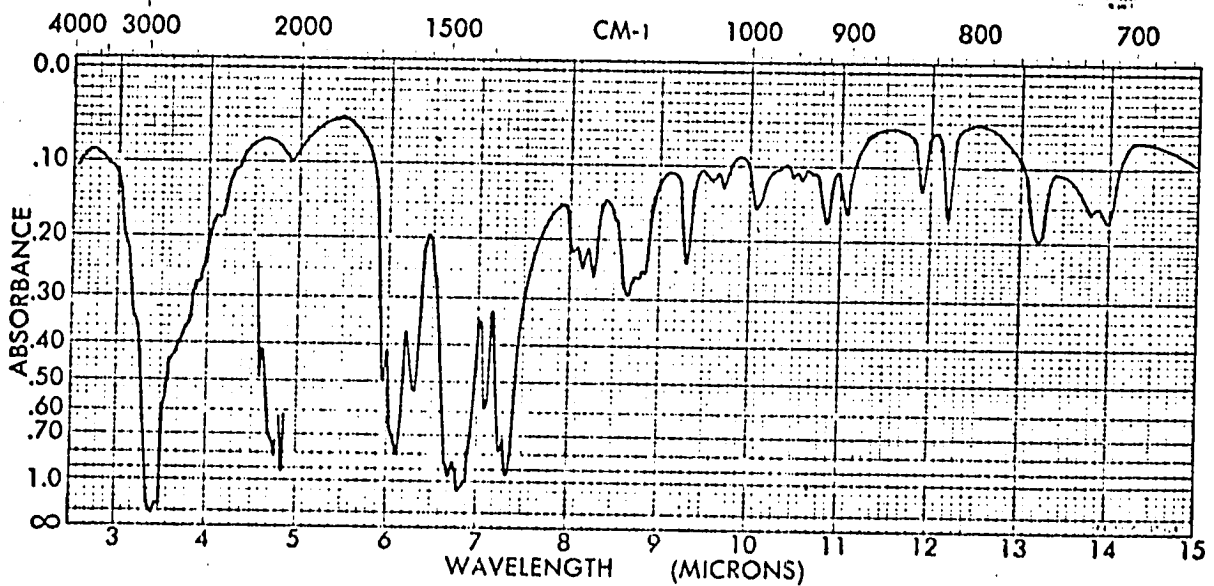
RECORDED & PUBLISHED BY
PERKIN-ELMER INSTRUMENT CO. INC.
800 NORTH BROAD STREET
ANN ARBOR, MICHIGAN 48106 U.S.A.



SPECTRUM NO.	ORIGIN	LEGEND	REMARKS
SAMPLE $\text{HO}-\text{C}_6\text{H}_4-\text{COOH}$		1.	6.24 μ Std. vs.
	PURITY	2.	5.8 μ Sample
	PHASE KBr Pellet	DATE	
	THICKNESS	OPERATOR	

SPECTRUM NO.

SAMPLE

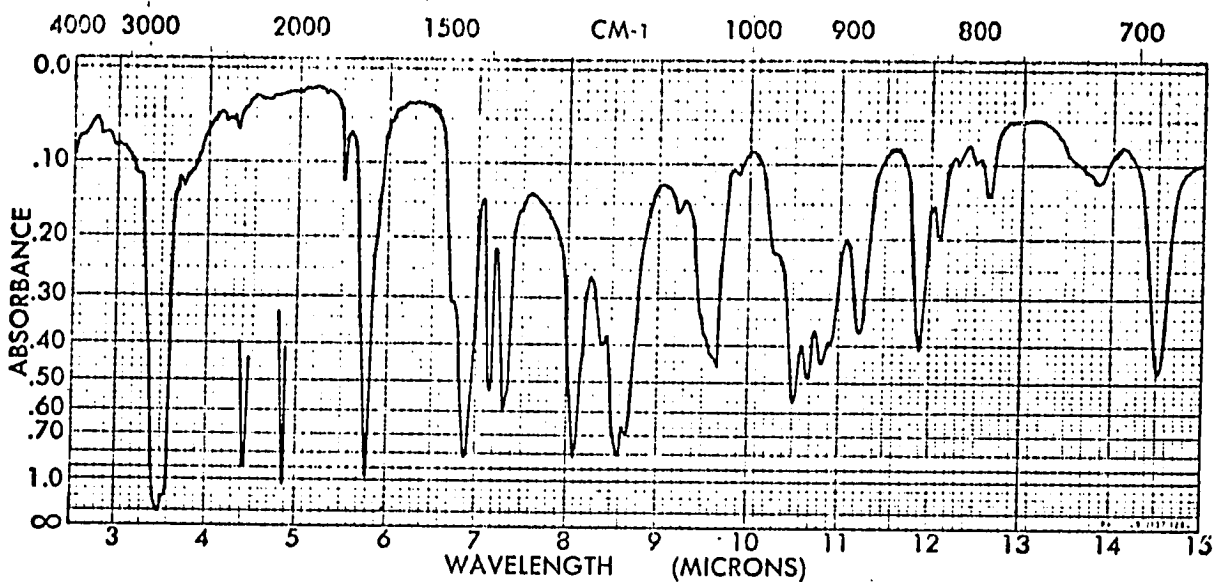


SPECTRUM NO.	ORIGIN	LEGEND	REMARKS
SAMPLE 151 $\text{R}-\text{N}^+(\text{R})_3-\text{COO}^-$		1.	6.24 μ Std. vs.
	PURITY	2.	6.1 μ Sample
	PHASE Nujol Mull	DATE	
	THICKNESS	OPERATOR	

SPECTRUM NO.

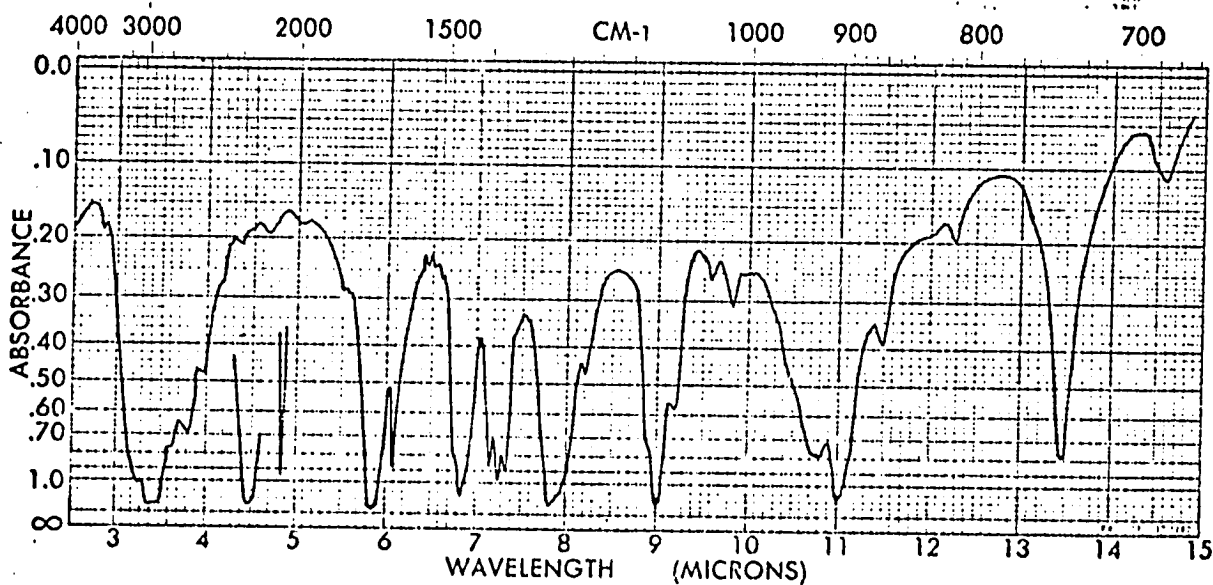
SAMPLE

PURCHASING UNIT
LABORATORY EQUIPMENT
DEPT. OF CHEMISTRY



SPECTRUM NO. <u>153</u>	ORIGIN _____	LEGEND _____	REMARKS _____
SAMPLE <chem>CC(=O)OC(C)OC(=O)C</chem>	PURITY _____	1. _____	6.24 μ Std. vs.
PHASE Nujol Mull	DATE _____	2. _____	5.8 μ Sample
THICKNESS _____	OPERATOR _____		

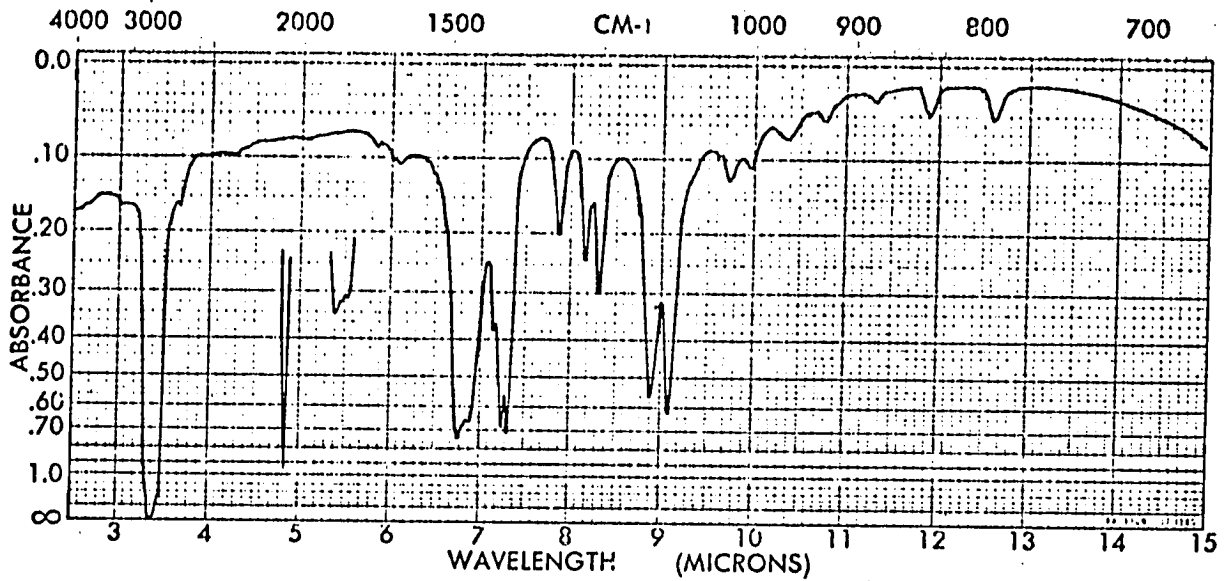
SPECTRUM NO. _____
SAMPLE _____



SPECTRUM NO. <u>156</u>	ORIGIN _____	LEGEND _____	REMARKS _____
SAMPLE <chem>CC(=O)O</chem>	PURITY _____	1. _____	6.24 μ Std. vs.
PHASE Nujol Mull	DATE _____	2. _____	5.9 μ Sample
THICKNESS _____	OPERATOR _____		

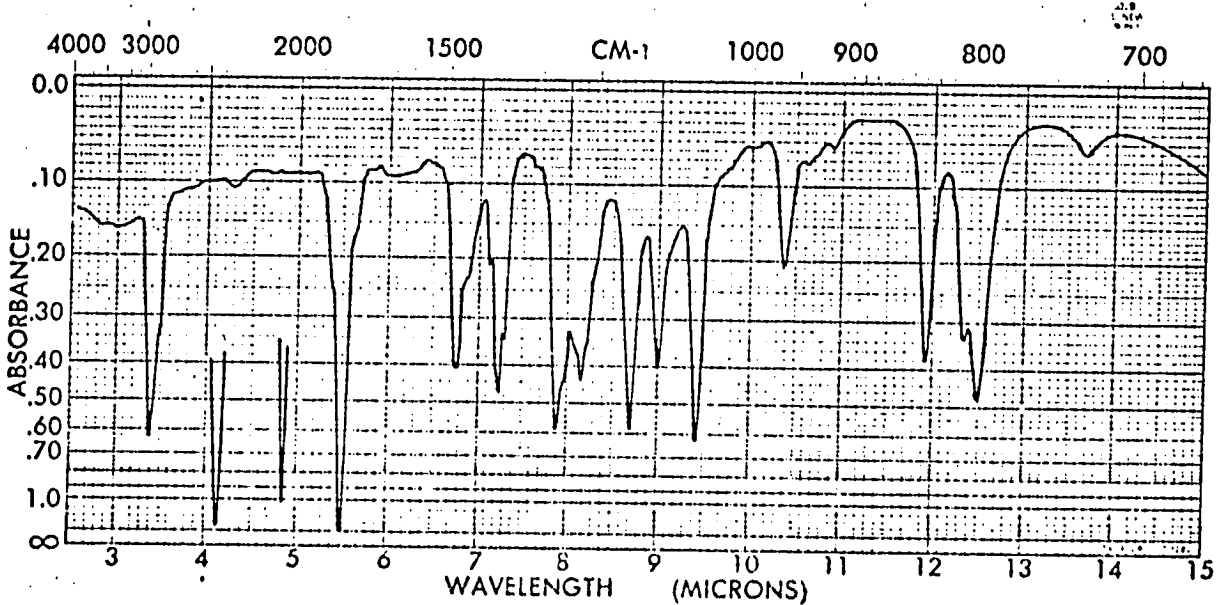
SPECTRUM NO. _____
SAMPLE _____

ESPECIFICALLY LABELED
PLAIN 5000-4000
C-1000-4000
C-1000-4000



SPECTRUM NO. _____	ORIGIN _____	LEGEND _____	REMARKS _____
SAMPLE <u>155</u>		1. _____	6.24 μ Std. vs.
<chem>C=C</chem>	PURITY _____	2. _____	6.8 μ Sample
	PHASE Neat	DATE _____	
	THICKNESS _____	OPERATOR _____	

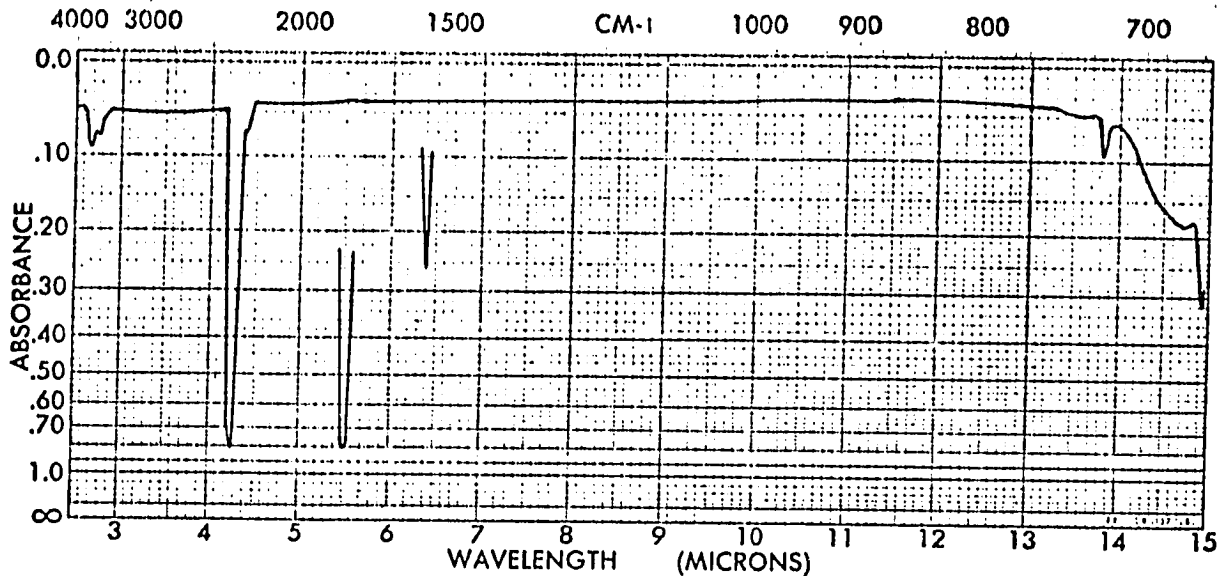
SPECTRUM NO. _____
SAMPLE



SPECTRUM NO. _____	ORIGIN _____	LEGEND _____	REMARKS _____
SAMPLE <u>157</u>		1. _____	6.24 μ Std. vs.
<chem>CC(=O)C</chem>	PURITY _____	2. _____	5.5 μ Sample
	PHASE Neat	DATE _____	
	THICKNESS _____	OPERATOR _____	

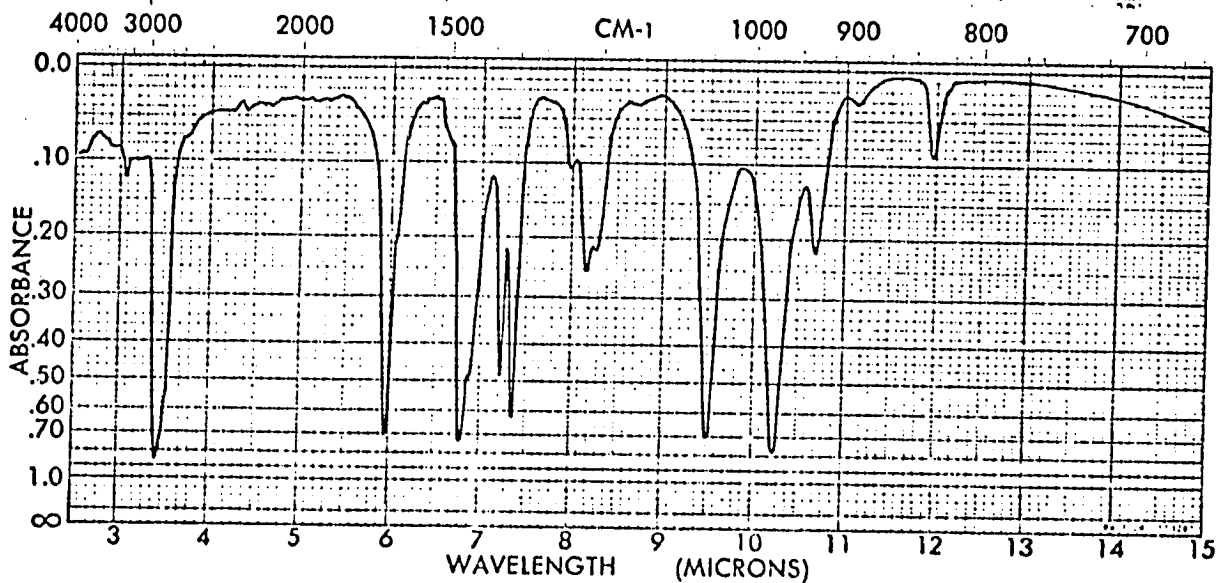
SPECTRUM NO. _____
SAMPLE

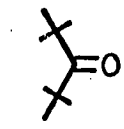
RECORDED BY _____
DATE _____



SPECTRUM NO.	ORIGIN	LEGEND	REMARKS
SAMPLE		1.	5.14 μ Std. vs.
CO ₂	PURITY	2.	4.3 μ Sample
	PHASE Vapor	DATE	
	THICKNESS	OPERATOR	

SPECTRUM NO.
SAMPLE



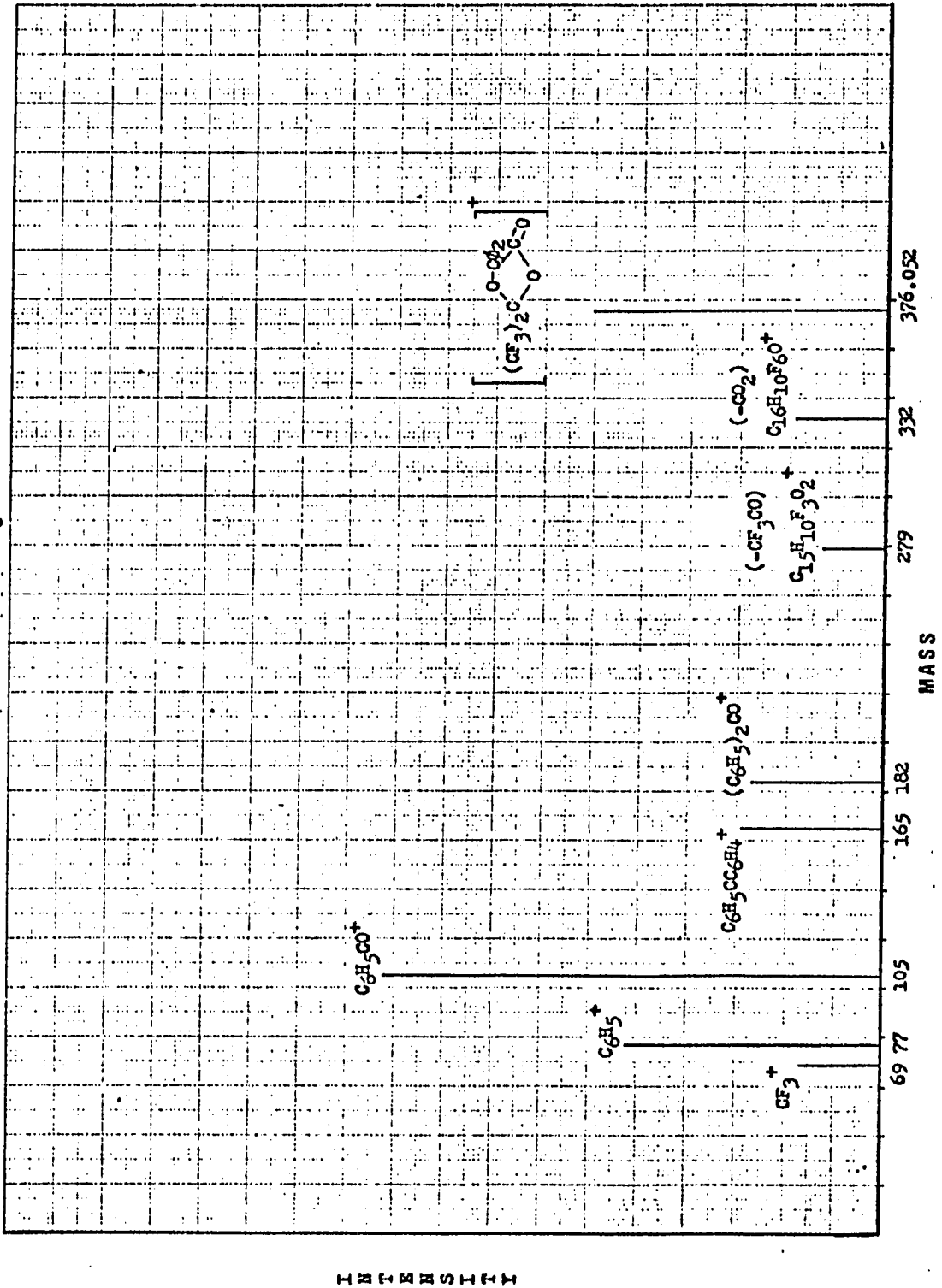
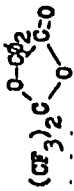
SPECTRUM NO.	ORIGIN	LEGEND	REMARKS
SAMPLE <u>154</u>		1.	
	PURITY	2.	
	PHASE Neat	DATE	
	THICKNESS	OPERATOR	

SPECTRUM NO.
SAMPLE

KOH...
SPECTRUM NO.

1/2" 10 X 10 TO THE CENTIMETER 46 1521
 10 X 10 CM.
 KEUFFEL & ESSER CO.

MASS SPECTRUM



INTENSITY